

NASA Technical Memorandum 103812

An Assessment of the Government Liquid Hydrogen Requirements for the 1995 - 2005 Time Frame Including Addendum, Liquid Hydrogen Production and Commercial Demand in the United States

July 1990

(NASA-TM-103812) AN ASSESSMENT OF THE
GOVERNMENT LIQUID HYDROGEN REQUIREMENTS FOR
THE 1995-2005 TIME FRAME INCLUDING ADDENDUM,
LIQUID HYDROGEN PRODUCTION AND COMMERCIAL
DEMAND IN THE UNITED STATES (NASA) ~~85~~ p 529328 98P N91-16160
--THRU-- N91-16168
Unclas 0309791
G3/28



National Aeronautics and
Space Administration

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TABLE OF CONTENTS

| <u>SUBJECT</u> | <u>PAGE</u> |
|---------------------------------|-------------|
| Acknowledgments | iii |
| Abbreviations and Acronyms | iv |
| Purpose | 1 |
| Scope | 1 |
| Authority | 1 |
| Introduction | 1 |
| Study Approach | 1 |
| Report Format | 2 |
| Program/Project Discussion | 3 |
| Kennedy Space Center | 3 |
| Stennis Space Center | 4 |
| Other NASA Centers | 5 |
| Vandenberg AFB | 6 |
| Edwards AFB | 6 |
| Department of Energy | 7 |
| Department of Commerce | 8 |
| Government Contractor Locations | 8 |
| The SEALAR Program | 9 |
| The HALE Program | 9 |
| The THESEUS Program | 10 |

ACKNOWLEDGMENTS

A number of information sources were used to obtain the data needed to develop this report. The personnel listed under "LH2 Development Study Distribution List" at the back of this report were contacted for any relevant data or information useful in the report development.

Data used in this report regarding the commercial production levels and market demands was obtained from the SRI International study under NASA-KSC Contract NAS10-11643.

ABBREVIATIONS AND ACRONYMS

| | |
|--------|--|
| AFB | Air Force Base |
| AFFTC | Air Force Flight Test Center (Edwards AFB) |
| ALDP | Advanced Launch Development Program |
| ALS | Advanced Launch System |
| CCAFS | Cape Canaveral Air Force Station |
| DFRF | Dryden Flight Research Facility |
| DOE | Department of Energy |
| EAFB | Edwards Air Force Base |
| HALE | High-Altitude Long-Endurance |
| JSC | Johnson Space Center |
| K | 1000 pounds |
| KSC | John F. Kennedy Space Center |
| LaRC | Langley Research Center |
| LeRC | Lewis Research Center (Cleveland, OH) |
| LH2 | Liquid Hydrogen |
| LO2 | Liquid Oxygen |
| MSFC | George C. Marshall Space Flight Center |
| NASA | National Aeronautics and Space Administration |
| NASP | National Aerospace Plane |
| NIST | National Institute of Standards and Technology |
| NOLA | New Orleans, LA |
| NTS | National Technical Systems |
| OBQ | On Board Quantity |
| OMV | Orbital Maneuvering Vehicle Project |
| P&W | Pratt & Whitney |
| R&D | Research & Development |
| RL-10 | Rocketdyne Engine |
| SEALAR | Sea Launch and Recovery Vehicle |
| SSC | Stennis Space Center |
| SSME | Space Shuttle Main Engine |
| STME | Space Transportation Main Engine |
| STS | Space Transportation System |
| TPD | Tons Per Day (730,000 #/yr) |
| VAFB | Vandenberg Air Force Base |
| WSTF | White Sands Test Facility |
| WTR | Western Test Range |

AN ASSESSMENT OF THE GOVERNMENT LIQUID HYDROGEN REQUIREMENTS FOR THE 1995 - 2005 TIME FRAME

PURPOSE

The purpose of this report is to present the results of a government study of long range liquid hydrogen (LH2) requirements for the time period of 1995 through the year 2005. The information in this report will be used to determine LH2 acquisition strategies to assure future availability of LH2 to support the variety of government programs as proposed.

SCOPE

The report reflects projected government LH2 consumption patterns and is presented in geographical as well as programmatic aspects. In addition, current LH2 production levels and the influence of the commercial marketplace is included based on data provided from a NASA/KSC contracted study with SRI International.

AUTHORITY

The Kennedy Space Center (KSC) is chartered to manage LH2 in support of all NASA programs and other government agency programs as prescribed by procurement regulations and mutual agreements.

INTRODUCTION

To assure an adequate supply of LH2 is available in support of various programs, it is imperative a long range projection of LH2 requirements be developed and maintained. This information is vital in the planning for necessary procurement actions and assuring adequate industry lead time to acquiring the necessary production and distribution capabilities.

STUDY APPROACH

A number of personnel were contacted representing various organizations having knowledge of potential LH2 needs in terms of technical aspects, program guidelines, schedules or other useful data to assemble consumption projections. It was predetermined that it would not be possible to guarantee LH2 amounts in specified time frames due to the typical dynamic behavior of program changes experienced from budget considerations and policy decisions. Optimistic as well as pessimistic projections were provided. The optimistic projection represents the LH2 requirements to current known schedules and contemplated projects being approved as currently proposed by the respective project office. The pessimistic projection is simply an arbitrary lower estimate on the part of the data source. Specific explanations are provided in the text.

The charting (exhibits) shows LH2 projections in tons per day (TPD) which equates to 730,000 pounds on an annual basis. Data was normalized on an annual basis. "Peaks" and "valleys" in site specific daily or monthly demands, although a very significant logistics concern, were not considered in this study.

REPORT FORMAT

The report content is structured in the following manner:

Program/Project Discussion

Each specific program or project is discussed regarding its scope, technical aspects, assumptions, method of data derivation, and scheduling information.

Data Display

Explanations are provided on the methods selected for displaying and summarizing the data.

Exhibit Discussion

A discussion is provided for each exhibit to orient the reader with the chart data.

Concluding Observations

PROGRAM/PROJECT DISCUSSION

KENNEDY SPACE CENTER

The LH2 requirements to support the space vehicle launch activity at KSC include the STS, Shuttle-C, and ALS programs plus the upper stage Centaur used with the Titan and Atlas vehicles at CCAFS.

Space Shuttle -- The projected launch rate is about 14 per year. Some indications are that this could be a mix of 11 STS and 3 Shuttle-C. According to MSFC a two engine and three engine version of the Shuttle-C is under consideration with preference for the three engine configuration. This study uses the three engine version thus the LH2 needs are essentially the same as STS for purposes of this study. In the outer years a rate of 14 STS and 4 Shuttle-C was used based on the February 1990 "Option 5 Manifest."

Based on the average consumption for STS flights 1 through 28R (30 launches) a quantity of 319,000 pounds of LH2/launch is used. Complex 39A and B storage tank combined annual boiloff loss is 216,000 pounds. About 20,000 pounds of LH2 per year is consumed for other support. A factor of 14% is used to account for losses due to transfer into KSC storage as delivered by trailer from the production source.

Centaur -- The Atlas/Centaur launch rate used is 4 per year. The Titan/Centaur rate is 4 per year.

A base support of 3,500 pounds/month and a launch quantity of 14,000 pounds are experienced for the Atlas/Centaur program; the similar quantities for the Titan IV program are 7,000 pounds/month and 23,000 pounds per launch. Adjusting for losses the total annual Centaur projection is 312,000 pounds.

Advanced Launch System -- For a programmatic discussion see the ALS program write-up. The reference vehicle (110K payload) with ten 580,000 pound thrust engines is used.

Assumption was made that the ALS would require two new launch pads at CCAFS or KSC. Each pad would require two 1.5 million gallon LH2 tanks. Initiation of tank test/fill in 1999 with the first launch in the year 2000. The LH2 on board quantity (OBQ) for the core is the same as the booster (221,400 pounds each). Using STS experience factors, the average consumption per vehicle flow is calculated at 797,000 pounds.

Pad tank loading loss is 14%. Total LH2 needed to purchase per launch is therefore 908,580 pounds. For this study 910,000 pounds is used.

Experience shows a 0.25 factor for pad tank annual boiloff including transfer/filling losses. Therefore this loss is calculated as 885,000 pounds/year (4 tanks). This value would be constant for each year. The launch rate (traffic model) is taken from a July 1989 manifest and slipped according to an April 1990 program review presentation, using 2 per year followed by 4 per year in the initial part of the program.

STENNIS SPACE CENTER

The LH2 requirements to support SSC include the on-going SSME testing for Space Shuttle with the addition of the ALS program involving thrust chamber, gas generator, turbopump assembly and main engine testing.

SSME – The SSME testing program (requalification) involves engine firings for a variety of test runs such as 1.5 seconds, 250 seconds, or 520 seconds duration. Usage per test is 50,000 pounds plus 147 pounds per second of test. The ongoing program is an "8 test" per month schedule. The quantity was calculated at 10,731,000 pounds per year and is used as a constant requirement for purposes of this study.

ALS – The product requirement for the proposed ALS program is dependent on the engine design chosen and amount of developmental work required, associated with the engine and its subcomponents. The flow rates and planned durations are normally known. Due to the nature of a hardware development program involving a sophisticated cryogenically fueled space vehicle engine actual test durations and number of tests needed are simply unpredictable. Using an experience base of engine development history and knowledge of the proposed engine basic performance characteristics a range of projections was however developed.

The STME engine proposed is a 580,000 pound thrust machine burning LH2 at the rate of 190 pounds per second. The same engine would be used in the Core vehicle as well as the Booster. First engine firings are planned for 1997 (ALDP Program Review, April 1990). Test durations include 180, 250, 620, and 780 second runs. Significant requirements to support component work assumed to start in 1996 based on the slippage in ALS timetable. The data is summarized in the following table. It is noted the SSC optimistic projection in 2002-2005 includes follow-on advanced work.

(K pounds typical)

| | <u>Optimistic</u> | <u>Pessimistic</u> |
|------|-------------------|--------------------|
| 1995 | --- | --- |
| 1996 | 15,000 | 7,545 |
| 1997 | 21,915 | 10,957 |
| 1998 | 57,040 | 28,520 |
| 1999 | 41,950 | 20,975 |
| 2000 | 50,340 | 25,170 |
| 2001 | 41,778 | 20,889 |

| | | |
|------|--------|--------|
| 2002 | 55,940 | 11,970 |
| 2003 | 55,940 | 11,970 |
| 2004 | 55,940 | 11,970 |
| 2005 | 55,940 | 11,970 |

OTHER NASA CENTERS

MSFC -- Estimated average is 350,000 pounds per quarter for the hydrogen/oxygen propulsion development program.

LaRC -- The NASP-GTE engine development program may require upwards of 442,400 pounds of hydrogen per year at this location in the 1995-1996 timeframe.

LeRC -- On site requirements are estimated at 255,000 pounds per year in support of the Cryogenic Fluids Technology Office projects, testing at the Plumbrook K site facility and Lunar/Mars related projects. Off site (contractors now unknown) needs are forecasted to be in the range of 125,000 pounds per year in support of the potential Lunar/Mars technology effort.

JSC -- Tests at the Thermochemical Test Area on the Shuttle Power Reactant Storage system and Shuttle LH2 recirculation pump acceptance after refurbishment is estimated at 12,000 pounds per year.

WSTF -- In consideration of Space Station and the proposed Lunar/Mars initiative the activities at the White Sands Test Facilities (test stands 302, 401, 404 and 405) could become substantial. Requirements would be for development and qualification of Space Transfer Vehicle, Lunar Excursion Vehicle, and Attitude Control System engines in a simulated space environment. The following estimate is provided:

(in K pounds)

| | |
|------|-----------------|
| 1995 | 500 |
| 1996 | 1,000 |
| 1997 | 6,000 to 10,000 |
| 1998 | 6,000 to 10,000 |
| 1999 | 6,000 to 10,000 |
| 2000 | 3,000 to 5,000 |
| 2001 | 1,000 |
| 2002 | 500 |
| 2003 | 500 |
| 2004 | 500 |
| 2005 | 500 |

DFRF -- A Structural Test Facility, using LH2, to perform thermal related tests on advanced airframe configurations is planned to be built by 1993/94. The initial work will be in support of the X-30 and NASP programs. For the timeframe of 1995 to 1999 the LH2 estimate is 300,000 pounds per year, and for 2000 through 2005, 150,000 pounds per year in support of potential advanced space vehicle structures research.

VANDENBERG AFB

Centaur -- Titan IV/Centaur launches are planned at VAFB. Three launches per year of the Titan IV are planned however only one is planned to have the Centaur upper stage. Based on experience of Centaur usage at CCAFS the VAFB estimate is 126,000 pounds per year.

ALS -- The ALS traffic model of July 1989 shows a normal mission scenario of 2 launches per year in 1998 and 1999 building to 3 to 4 in 2000 and beyond for the Western Test Range (WTR). In view of the program change (April 1990) with the first launch in early 2000 (presumably from KSC) the WTR schedule is shifted accordingly. The same pad configuration is assumed as that planned at KSC. Tank fill is assumed in 2000 and 2 flights per year in 2001 and 2002 building to 4 in 2003 through 2005. See KSC ALS discussion for detail derivations.

Summary of Data (K pounds) Total for VAFB

| | |
|------|-------|
| 1995 | 126 |
| 1996 | 126 |
| 1997 | 126 |
| 1998 | 126 |
| 1999 | 126 |
| 2000 | 569 |
| 2001 | 2,459 |
| 2002 | 2,459 |
| 2003 | 4,349 |
| 2004 | 4,349 |
| 2005 | 4,349 |

EDWARDS AFB

Other than the DFRF, previously identified, two other locations at EAFB in the planning for LH2 use are the Astronautics Laboratory and the Ground Support System to support the X-30 at the Air Force Flight Test Center (AFFTC). (See also the HALE Program.)

Astro Lab -- The 2A Facility will be used to test the Thrust Chamber Assembly and Gas Generator for advanced propulsion concepts. The 3,800 gallon run tank and 28,000 gallon storage tank will be used for LH2. Plans called for 340,000 to 1,220,000 pounds of LH2 per year prior to 1994. In view of ALS programmatic changes it appears the requirement will slip into 1995/1996 timeframe. An annual average of 600,000 pounds was used in this study.

AFFTC -- The LH2 Ground Support System size will depend on the vehicle configuration selected. Under consideration is what is known as the 1X payload and the 4X payload. In the case of the 1X there are two 900,000 gallon tanks proposed to support LH2 requirements. For

the 4X two 1,500,000 gallon tanks are proposed. The on-board quantity for 1X is about 120,000 pounds and for the 4X about 200,000 pounds. For this study activation of the ground system was assumed for 1996 with the first flight in 1997. To determine the effect on LH2 requirements during 1999 through 2002 a low and high range were picked to establish the range magnitude. The range looked at is for a 1X at 20 flights per year over 4 years at 165,000 pounds per flight (allowing for losses) which equated to 3,300,000 pounds per year. The other is for a 4X at 40 flights per year over 4 years at 280,000 pounds per flight, equating to 10,200,000 pounds per year. For 2003 through 2005 a range of 825,000 to 2,800,000 pounds of LH2 was selected (no data source) representing 5 to 10 operational flights per year (1X and 4X respectively).

DEPARTMENT OF ENERGY

The DOE has a number of research plants and laboratories engaged in projects requiring bulk gaseous hydrogen (delivered as liquid) and some direct liquid requirements. The following summarizes these requirements and locations.

West Coast

Los Alamos, NM

The most significant demand for LH2 at this location is in support of the proposed Ground Test Accelerator Program. It is anticipated needs will start in 1991 during initial tests of the 28,000 gallon storage system but will climb to one to three million pounds per year by the mid 1990's. Optimistic longevity of the program is 1999.

Stanford, CA

Support at the high energy lab has historically run at 14,000 to 27,000 pounds of LH2 per year and is anticipated to continue at this level.

East Coast

Pinellas Plant, FL

Although LH2 projections are in the range of 10,000 pounds per year for operation of the furnaces for manufacturing electronic piece parts, the historical consumption has reached annual levels of 150,000 pounds.

Bettis Lab
West Mifflin, PA

The materials technology project has had a small requirement for LH2 at about 1,000 pounds/year, but is expected to increase at a 5% rate/year through the time frame of this study.

Knolls Lab
Schenectady, NY

The projection at this atomic power facility is 5,000 pounds/year.

Brookhaven Lab
Long Island, NY

Usage for the high energy particle accelerator is estimated between 8,000 to 21,000 pounds per year.

DEPARTMENT OF COMMERCE

A variety of projects involving slush hydrogen, thermal conductivity and heat transfer are conducted at the National Institute of Standards and Technology (NIST) in Boulder, Colorado. Overall requirements are about 7,000 pounds/year.

GOVERNMENT CONTRACTOR LOCATIONS

Pratt & Whitney
West Palm Beach, FL

Annual estimates are:

| | |
|-------|----------------------------|
| RL-10 | 110,000 pounds |
| SSME | 200,000 pounds (1994-1997) |
| ALS | 160,000 pounds (1994-1999) |
| | 200,000 pounds (2000) |
| | 100,000 pounds (2001-2005) |
| NASP | 40,000 pounds (1994-1998) |
| | 20,000 pounds (1999-2000) |

Wyle Laboratories
Norco, CA

A range of 180,000 to 266,000 pounds per year was used in this study.

General Dynamics
San Diego, CA

A range of 105,000 to 195,000 pounds per year was used in this study.

Other locations and their annual estimates (pounds) are as follows:

Aerojet Tech Systems Co.
Sacramento, CA

30,000 - 70,000

Ball Aerospace
Berthoud, CO

28,000

Martin Marietta
Denver, CO

10,000

National Technical Systems
Saugus, CA

0 - 10,000

Rockwell International
Downey, CA

24,000

Rocketdyne
Santa Susana, CA

100,000 - 200,000

THE SEALAR PROGRAM

Called the Sea Launch and Recovery (SEALAR) vehicle, this system would be composed of two stages, each powered by a pressure-fed liquid propellant engine. The entire vehicle would be floated out to sea prior to lift-off. The stages would be recovered and refurbished. The 110 foot tall rocket first stage would be fueled with RP/LO2 and second stage LH2/LO2. The OBQ for LH2 is 22,000 pounds. First launch is planned for 1997/1998 (recent momentum on program could accelerate first full configuration vehicle test). Plans are to start with a launch per quarter building to six per month in eight years. Honolulu, San Diego, Galveston and Jacksonville are potential LH2 loading ports, with San Diego as most likely.

For this study it was assumed all LH2 requirements would be based out of San Diego at the following rate (30,000 pounds per flight was used):

| | <u>Launches</u> | <u>Optimistic</u> | <u>Pessimistic</u> |
|------|-----------------|-------------------|--------------------|
| 1997 | R&D | 100,000 | 100,000 |
| 1998 | 4 | 120,000 | 120,000 |
| 1999 | 12 | 360,000 | 360,000 |
| 2000 | 21 | 630,000 | 630,000 |
| 2001 | 29 | 870,000 | 870,000 |
| 2002 | 38 | 1,140,000 | 870,000 |
| 2003 | 46 | 1,380,000 | 870,000 |
| 2004 | 55 | 1,650,000 | 870,000 |
| 2005 | 63 | 1,890,000 | 870,000 |

THE HALE PROGRAM

Called the High-Altitude Long-Endurance (HALE) unmanned aircraft, this system is planned to provide a capability to operate for extended periods of time at very high altitudes to provide continuous reconnaissance, surveillance, communications, and targeting functions.

Each HALE aircraft flight would require 24,000 pounds of LH2. Endurance would be up to five days. R&D efforts are assumed for EAFB. Operational fueling sites are planned in Arizona, Nevada and Utah.

The operational capacity in the 2002 to 2005 timeframe is phenomenal with 43 aircraft servicing what is known as the inner line and 18 on the outer line. This schedule poses a significant demand on LH2 production and distribution. The following demand forecast was derived:

| | |
|------|---------|
| 1994 | 10,000 |
| 1995 | 70,000 |
| 1996 | 130,000 |
| 1997 | 190,000 |

| | |
|------|--------------------------|
| 1998 | 250,000 |
| 1999 | 310,000 |
| 2000 | 320,000 |
| 2001 | 430,000 |
| 2002 | 500,000 |
| 2003 | 6,000,000 |
| 2004 | 6,000,000 to 50,000,000 |
| 2005 | 6,000,000 to 117,530,000 |

Assume 1994 through 2002 as requirements out of EAFB for developmental work and flight support until fueling sites are set up in other states.

THE THESEUS PROGRAM

The Theseus is a long-range, very high altitude aircraft using fuel cell propulsion and capable of conducting worldwide chemistry, radiation, and dynamics experiments. It is planned that the aircraft would be usable by 1994/1995. The LH2 OBQ is 500 to 1,000 pounds. DFRF would probably be the test bed for development and testing, with operational flights out of government facilities (Wallops, KSC, National Science Foundation Balloon Facility in Texas, New Mexico, etc.).

Requirements are estimated at 100,000 pounds per year at DFRF during 1994-1995. 50,000 pounds per year is estimated out of the West Coast and the same from the East Coast for 1996 through 2005.

THE ADVANCED LAUNCH SYSTEM

Air Force and NASA have identified needs in the late 1990s for a new space launch system for cargo transport which requires substantially improved reliability, operability and economy over current systems. The concept proposed is known as the Advanced Launch System (ALS) and is envisioned as a family of vehicles for a new generation launch system providing a capability for delivering a range of cargo sizes up to 220,000 pounds into low Earth orbit. The baseline family is a LO2/LH2 propelled vehicle using a 580,000 pound thrust (vacuum) engine in clusters according to vehicle sizing requirements. The model designated as ALS-80K is a lower range payload weight capability using a stage and one-half technique. The ALS-120K models use a parallel burn staging technique for heavier missions. The ALS-120K uses a core vehicle with an attached booster or boosters (ALS-300K).

This study uses the ALS-120K with a core and single booster, sometimes referred to as the baseline or reference vehicle. The vehicle LH2 tank size is essentially identical for the core and booster. The launch pad configuration varies among the studies but essentially predict the need for very large LH2 storage tanks (over one million gallons).

This study assumes two 1.5 million gallon tanks at each pad. The basis for this selection is twofold. First, it is understood from a well-known tank manufacturer that a 1.5 million gallon cryogenic sphere is about the sensible limit. The other factor is that with this size storage, sufficient product is on hand to accommodate a number of scrub turnarounds and launch two vehicles within two days of each other. Ullage, losses, and a thermal buffer are also accounted for in the chosen configuration. Additionally, the selection seems to fit the apparent DOD move towards a smaller vehicle with a high launch frequency and the NASA desire for a heavy lift launch vehicle (HLLV) but at a lower launch frequency.

OTHER POSSIBILITIES

| | |
|--------------------|--|
| Arnold AFB, TN | The LH2 facility at Tullahoma may be activated (and expanded) to accommodate component testing. |
| Livermore Labs, CA | The hydrogen gas coil gun may demand LH2 for economies (as compared to gas recovery). |
| Hawaii Launch Site | Assume LH2 requirements would be met locally. |
| Japanese H-2 | Under consideration for U.S. deployment in competition with other vehicles. |
| The Shuttle Z | A proposed Shuttle derived heavy lift vehicle requiring a new major engine development effort. |
| The Shuttle T | Due to limited cargo bay volume in the Shuttle C to accommodate in-space LH2 fueling, a tanker vehicle has been proposed. The Shuttle T concept would lift 43 metric tons of LH2 for each mission (lunar). |
| The SSX | The SSX launcher is a totally reusable rocket powered by the Pratt & Whitney RL-10 engine. |
| NASP | The requirements to support early testing of NASP engine configurations in terms of quantity and location is not yet defined but could be significant. |
| Delta Upper Stage | A high energy upper stage using LH2 is on the drawing boards. A CCAFS site has been proposed. |

U.S. Hydrogen Energy Economy

Subject to pending legislation DOE and NASA may be requested to engage in R&D projects to promote non-fossil derived LH2 production and commercial aircraft utilization of LH2 as a fuel. Increased environmental concerns, fossil fuel limitations, and international competition for energy applications could inspire increased use of hydrogen.

Commercial Demand

The variety of goods and services using hydrogen (currently 9,000,000 tons annually) is anticipated to grow. The LH2 demand (currently 30,000 tons) is anticipated to grow accordingly due to its transport economics to support the commercial industries. The SRI study under KSC contract shows this growth pattern.

Miscellaneous

Further coordination is needed at some potential sites such as Colorado Springs, TRW at Redondo Beach, CA (OMV project) and programs such as the Naval Unmanned Aerial Vehicle (UAV) projects.

DATA DISPLAY

Historically LH2 contracting has been split between what has been termed "West Coast" and "East Coast." The reason for this was simply due to the fact that production and major consuming sites were either concentrated in the California area or in the Mississippi/Alabama/Florida region. Today the West Coast contract provides LH2 services to California, New Mexico, and Colorado sites from a production plant near Los Angeles. The East Coast contract serves Texas, Mississippi, Alabama, Florida, Virginia, and Ohio consuming sites from a production source in New Orleans. Typically the major space program needs have concentrated at the engine test site in Mississippi (Stennis Space Center) and at the launch site in Florida (Kennedy Space Center). In view of these factors the data has been summarized and displayed as shown in the following exhibits.

EXHIBIT DISCUSSION

Exhibit A -- This exhibit shows the LH2 projection in tons per day at the Kennedy Space Center. The Shuttle launch requirements are depicted in the range of 9 to 14 launches per year. The Shuttle launch rate of 14 could include 11 manned and 3 cargo configurations. The proposed Shuttle-C with LH2 payloads is shown at a launch rate of 4 per year. The influence of the Atlas Centaur and Titan Centaur launches from Cape Canaveral Air Force Station is shown at a total predicted rate of 8 per year. Assuming the first ALS launch is in the year 2000 the influence of a launch rate of 2 and then 4 per year is illustrated.

Exhibit B -- This exhibit shows the LH2 projection in tons per day at the Stennis Space Center. The Shuttle SSME engine testing is predicted at a constant level. The significant influence of the proposed ALS program is illustrated with the "high" number indicating the optimistic projection and the "low" as the pessimistic evaluation.

Currently the SSC requirements are being met by barging product from a nearby production plant. Shown is the current/planned capacity of this plant (NOLA). Based on SRI data for on-stream factors and plant utilization factors the production to support government and commercial requirements is plotted as a reference band. It is noted that about 30 TPD is routinely committed to commercial accounts.

Exhibit C -- This exhibit shows the tally of all government LH2 projections in tons per day for the using sites (sites east of the Mississippi River plus JSC) under a potential East Coast contract (or contracts).

The KSC data is the range of projections similarly shown in Exhibit A but in bar graph form. Likewise the SSC data (Exhibit B) is also shown in bar graph form. The "other" government data is in the range of 3 to 4 tons per day and includes MSFC, LeRC, LaRC, JSC, P&W, DOE, and Theseus.

As was shown in Exhibit B production capacity plots are also indicated. This includes the current producing sites in New Orleans, LA, Ashtabula, OH, and Niagara Falls, NY. Although there are production sources in Canada these are not only outside of the United States but were sized and built primarily for Northeast U.S. and Canadian commercial markets, and therefore are not considered significantly influential for government support. The effect however is shown by the North American East Coast capacity band. Also plotted is the SRI data on commercial demand through the year 2000.

Exhibit D -- This exhibit shows the tally of all government LH2 projections in tons per day for the using sites under a potential West Coast contract (or contracts).

For this exhibit the data is displayed in more of a programmatic form. The NASA needs include the numerous small consuming locations at the contractor sites at Aerojet, Rockwell, Wyle, General Dynamics, Ball, NTS, and Martin Marietta. Also in this category the requirements at DFRF and WSTF are included. The NASP is shown separately due to its potential significance and primary location at EAFB.

The other government requirements include VAFB, HALE, DOE, Department of Commerce (NIST), and SEALAR.

Also referenced are the LH2 production capacities and projected commercial demands. The producing plants include the existing facilities at Sacramento, CA and Ontario, CA.

Exhibit E -- This exhibit shows the total U. S. government LH2 projection in tons per day and illustrates the combination of Exhibit C (East Coast) and Exhibit D (West Coast) data. For reference purposes the total U. S. LH2 production capacity is shown as well as the total production in North America.

The term "high" was selected to show the tally of all optimistic projections and the "low" as the tally of all program projections on a reduced scale.

Exhibit F -- This exhibit is Exhibit E data with an overlay of commercial demand and its combined influence with the government projection.

EXHIBIT A KSC LH₂ PROJECTION

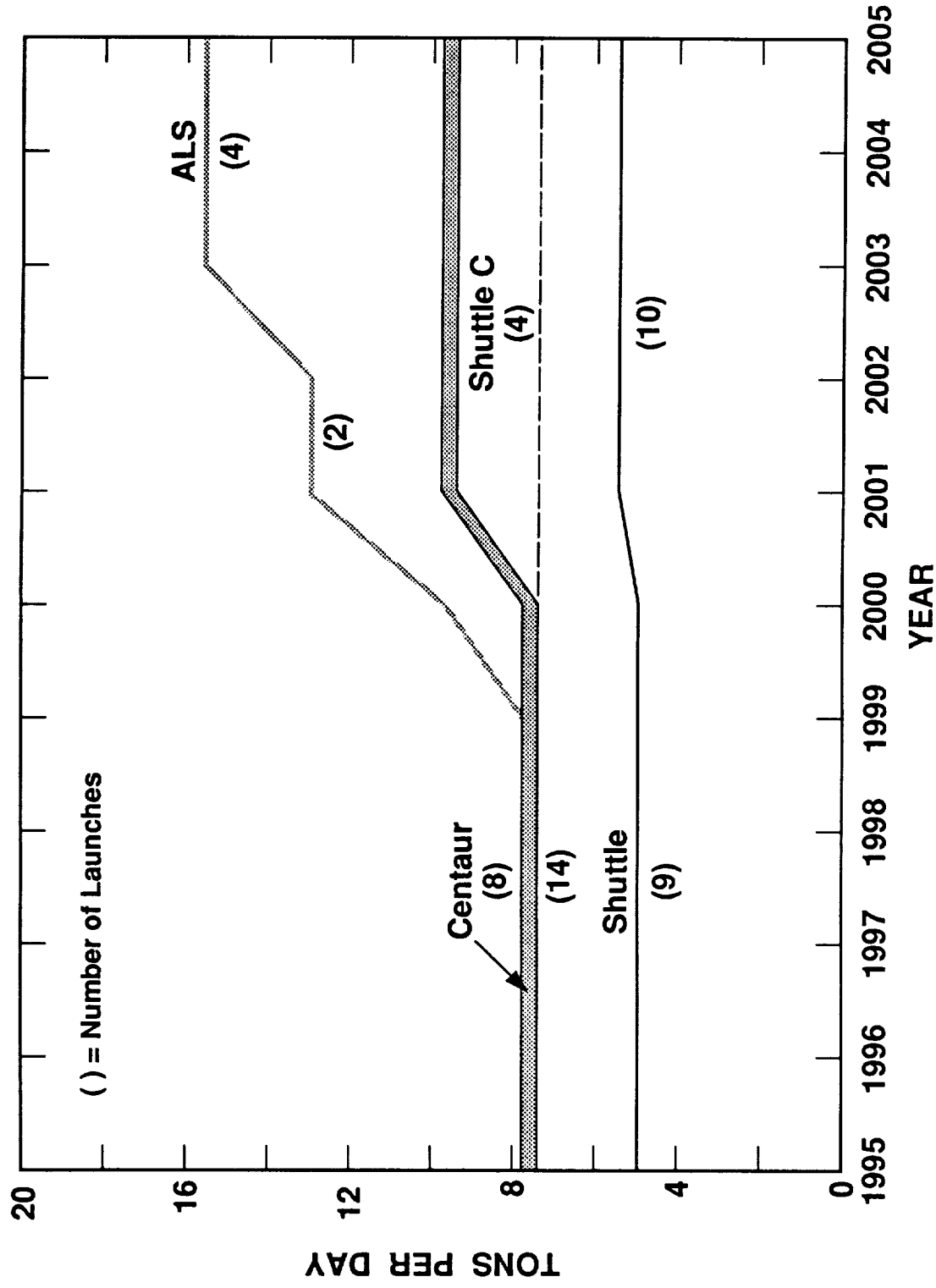
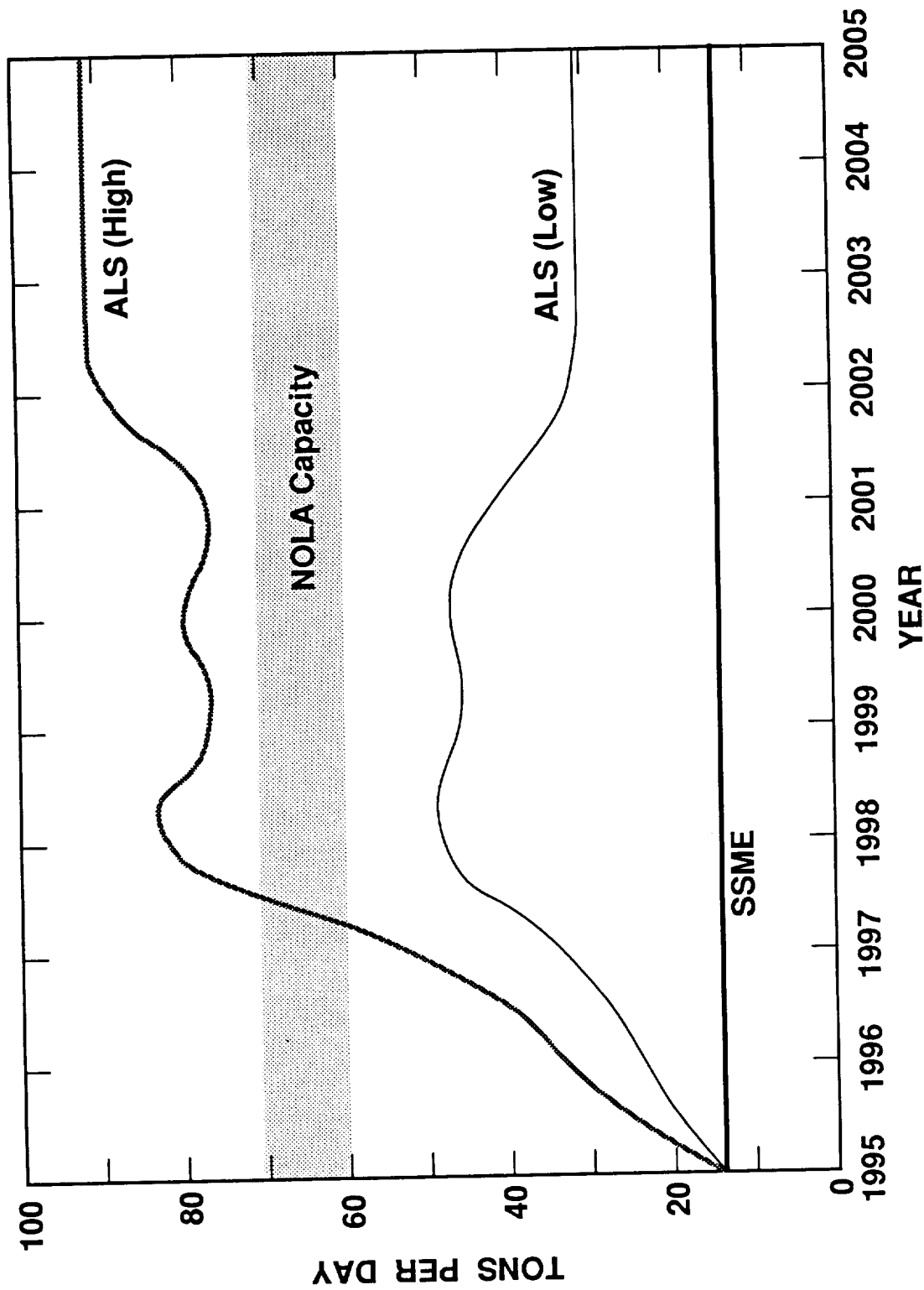
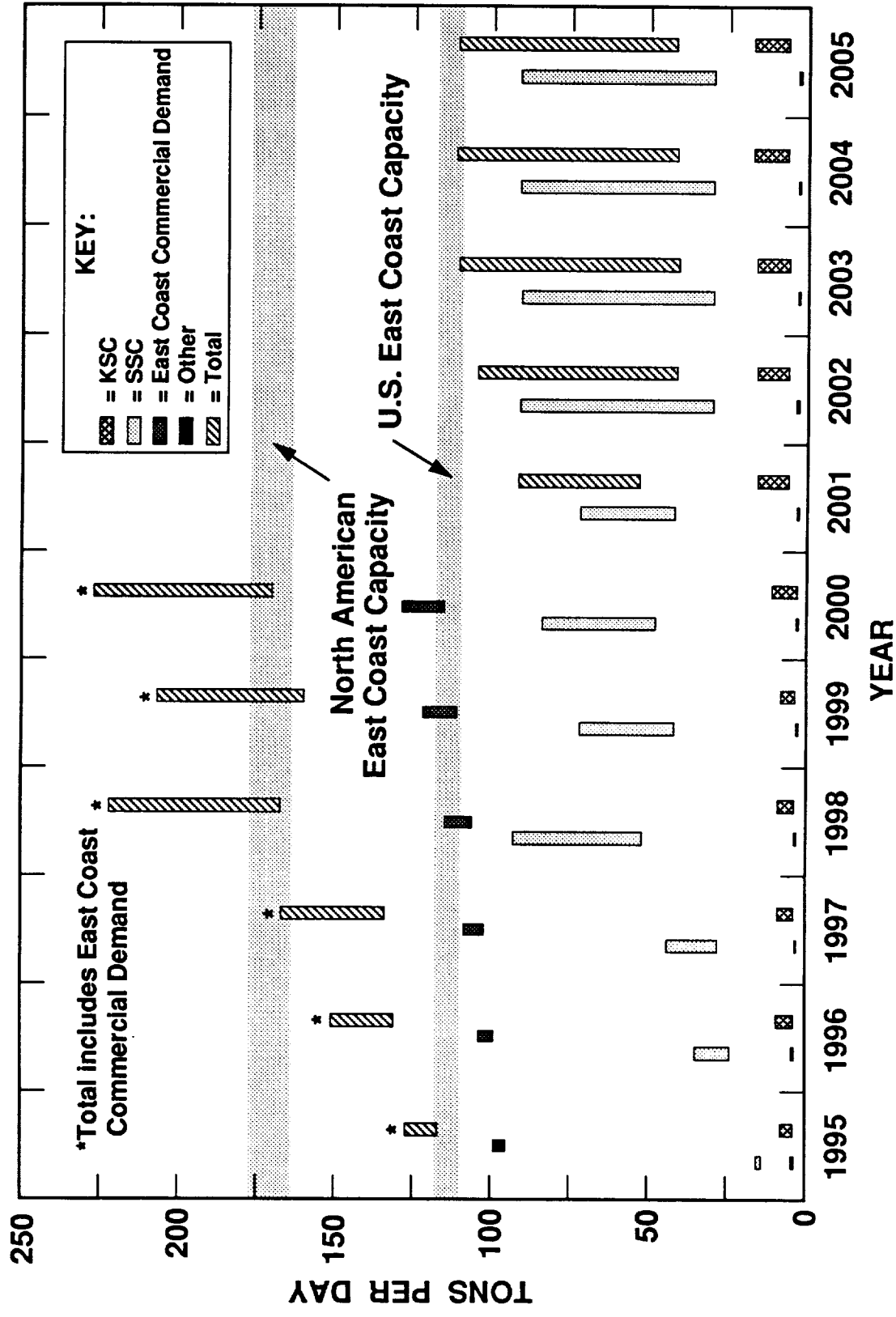


EXHIBIT B SSC LH₂ PROJECTION



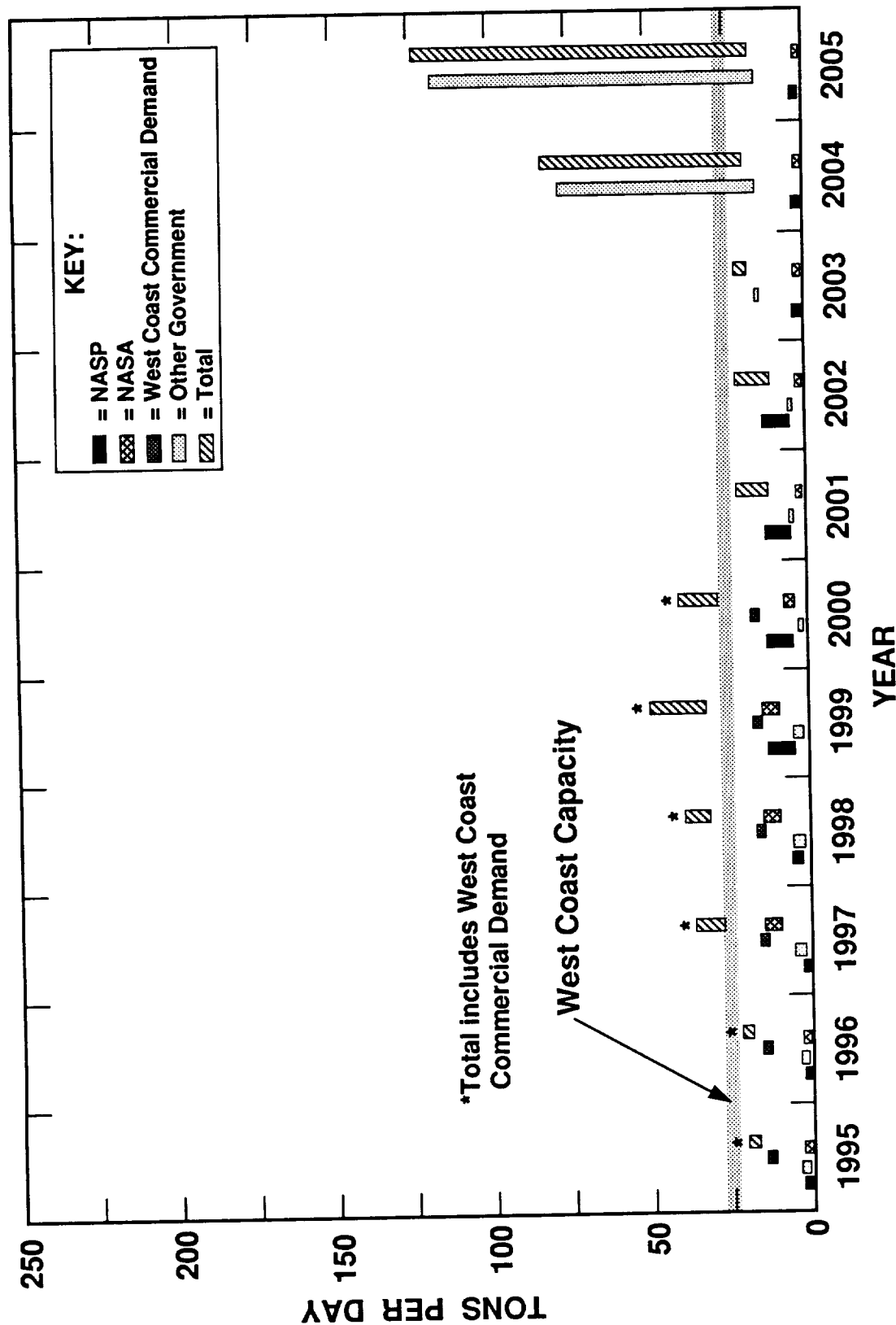
SRI International

EXHIBIT C GOVERNMENT EAST COAST LH₂ PROJECTION



SOURCES: NASA (government demand) and SRI International (all other data).

EXHIBIT D GOVERNMENT WEST COAST LH₂ PROJECTION



SOURCES: NASA (government demand) and SRI International (all other data).

SRI International

EXHIBIT E GOVERNMENT TOTAL U.S. LH₂ PROJECTION

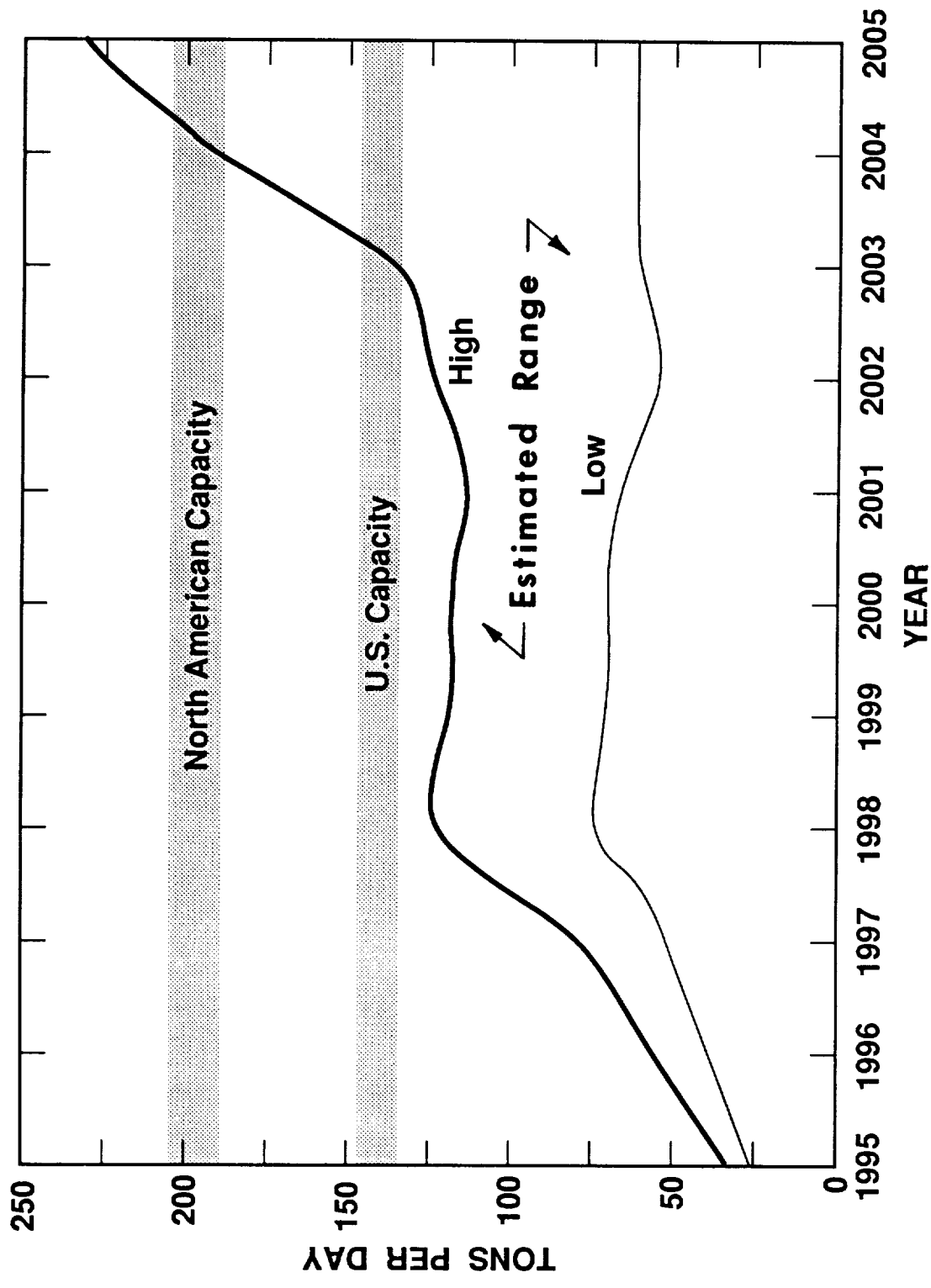
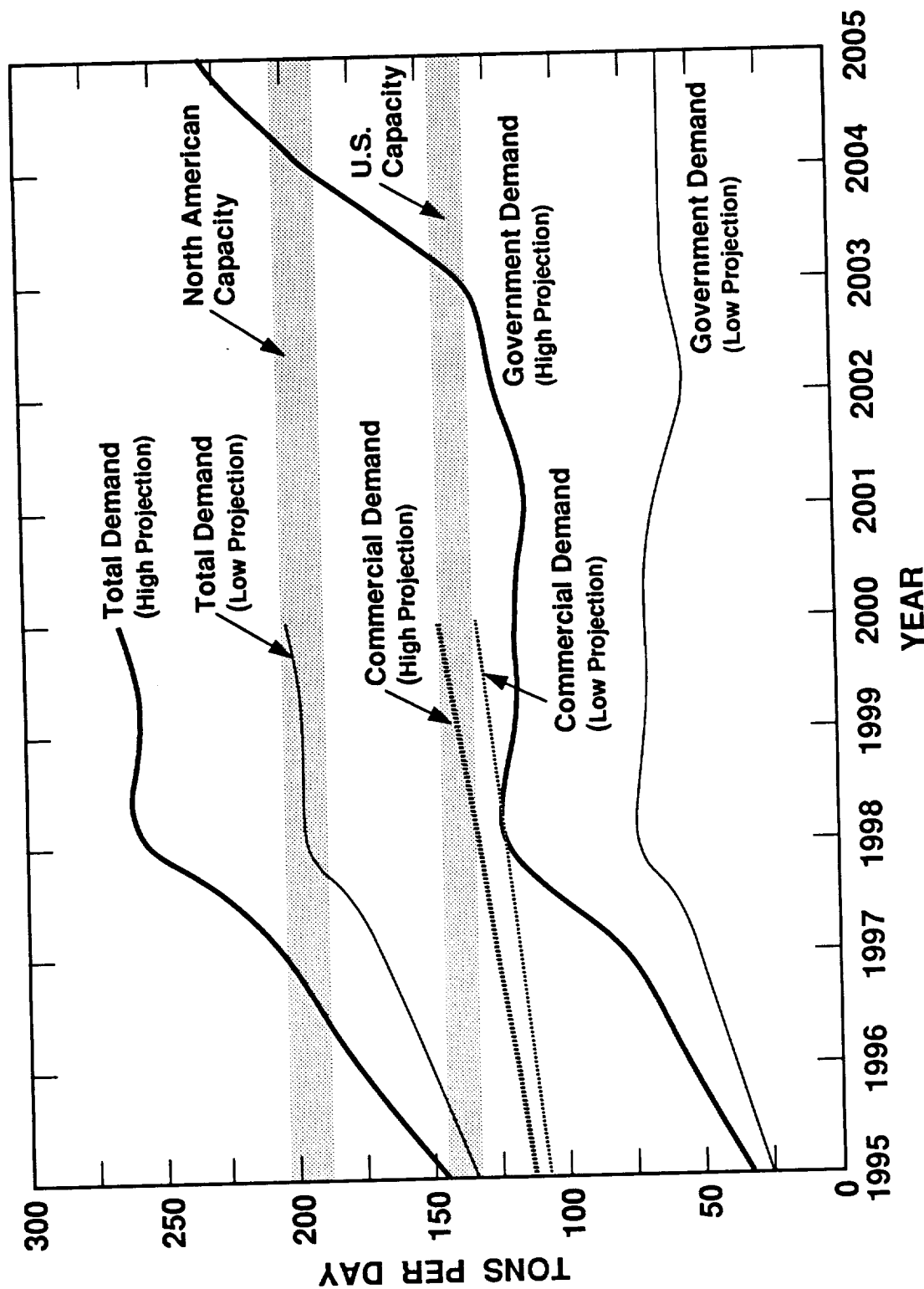


EXHIBIT F TOTAL U.S. LH₂ PROJECTION



SOURCES: NASA (government demand) and SRI International (all other data).

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CONCLUDING OBSERVATIONS

1. The ALS and HALE programs may represent the predominant government needs for LH2 in the long range. The extreme dispersion in predicted requirements for both of these programs however make the LH2 acquisition strategy selection difficult.
2. The data as assembled for this initial report clearly indicates a need for KSC constant program/project surveillance and close coordination with those organizations. Also clear is the need for KSC to monitor industry's plans for LH2 plant production and distribution expansion.
3. The uncertainty over the scope and location of the multitude of projects and programs make quantifying the demand for a critical fuel such as hydrogen extremely difficult. The need for a focused effort and continued close collaboration with all users and LH2 producers is evident.

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Final Report • July 1990

SRI Project 8562

LIQUID HYDROGEN PRODUCTION AND COMMERCIAL DEMAND IN THE UNITED STATES

Prepared for:

JOHN F. KENNEDY SPACE CENTER
National Aeronautics and Space Administration
Procurement Office

CONTENTS

| | |
|---|----|
| EXECUTIVE SUMMARY | 1 |
| INTRODUCTION AND METHOD OF APPROACH..... | 1 |
| CONCLUSIONS | 3 |
| Liquid Hydrogen Producers | 3 |
| Consumption..... | 6 |
| INTRODUCTION | 9 |
| LIQUID HYDROGEN PRODUCERS | 11 |
| LIQUID HYDROGEN CONSUMPTION | 18 |
| MARKET OVERVIEW | 18 |
| CHEMICALS, PETROCHEMICALS, AND REFINING | 21 |
| Chemical, Petrochemicals, and Refining Applications..... | 22 |
| Hydrogen Sources for Chemical, Petrochemicals, and Refining Uses | 22 |
| Regional Consumption | 22 |
| Trends in Consumption for Chemical, Petrochemicals, and Refining Uses | 23 |
| METALS..... | 23 |
| Metal Applications..... | 24 |
| Hydrogen Sources for Metal Uses | 25 |
| Regional Consumption | 25 |
| Factors Affecting Consumption for Metal Uses | 25 |
| ELECTRONICS | 25 |
| Electronic Applications | 26 |
| Hydrogen Sources for Electronics Uses..... | 28 |
| Regional Consumption | 28 |
| Factors Affecting Consumption for Electronic Uses..... | 28 |
| FATS AND OILS..... | 28 |
| Fats Applications | 29 |
| Hydrogen Sources for Fats Uses..... | 29 |
| Regional Consumption | 30 |
| Factors Affecting Consumption for Fats Uses..... | 30 |

CONTENTS (Concluded)

| | |
|---|----|
| GLASS..... | 31 |
| Glass Applications | 31 |
| Hydrogen Sources for Glass Uses..... | 31 |
| Regional Consumption | 32 |
| Factors Affecting Consumption for Glass Uses..... | 32 |
| OTHER USES | 33 |

LIST OF TABLES

| | | |
|------|--|----|
| ES-1 | North American Liquid Hydrogen Producers | 4 |
| ES-2 | U.S. Commercial Market for Liquid Hydrogen..... | 6 |
| ES-3 | U.S. Liquid Hydrogen Markets in 1989 by Geographic Region..... | 7 |
| 1 | North American Liquid Hydrogen Producers | 12 |
| 2 | U.S. Consumption of Hydrogen-1989 | 18 |
| 3 | U.S. Commercial Market for Liquid Hydrogen..... | 20 |
| 4 | Liquid Hydrogen Consumption in the Chemical, Petrochemicals, and Refining Industries..... | 21 |
| 5 | Hydrogen Consuming Chemicals, Petrochemicals | 22 |
| 6 | Liquid Hydrogen Consumption in Metals..... | 24 |
| 7 | Liquid Hydrogen Consumption in Electronics | 26 |
| 8 | Applications for High-Purity Hydrogen in Semiconductor Manufacturing | 27 |
| 9 | Liquid Hydrogen Consumption in Fats and Oils..... | 29 |
| 10 | Liquid Hydrogen Consumption in Float Glass..... | 31 |
| 11 | Other Consumption of Hydrogen | 33 |

LIST OF FIGURES

| | | |
|------|--|----|
| ES-1 | Liquid Hydrogen Consuming Regions..... | 2 |
| 1 | Liquid Hydrogen Consuming Regions..... | 10 |
| 2 | East Coast Liquid Hydrogen Projection..... | 15 |
| 3 | West Coast Liquid Hydrogen Projection..... | 16 |
| 4 | Total U.S. Liquid Hydrogen Projection..... | 17 |

EXECUTIVE SUMMARY

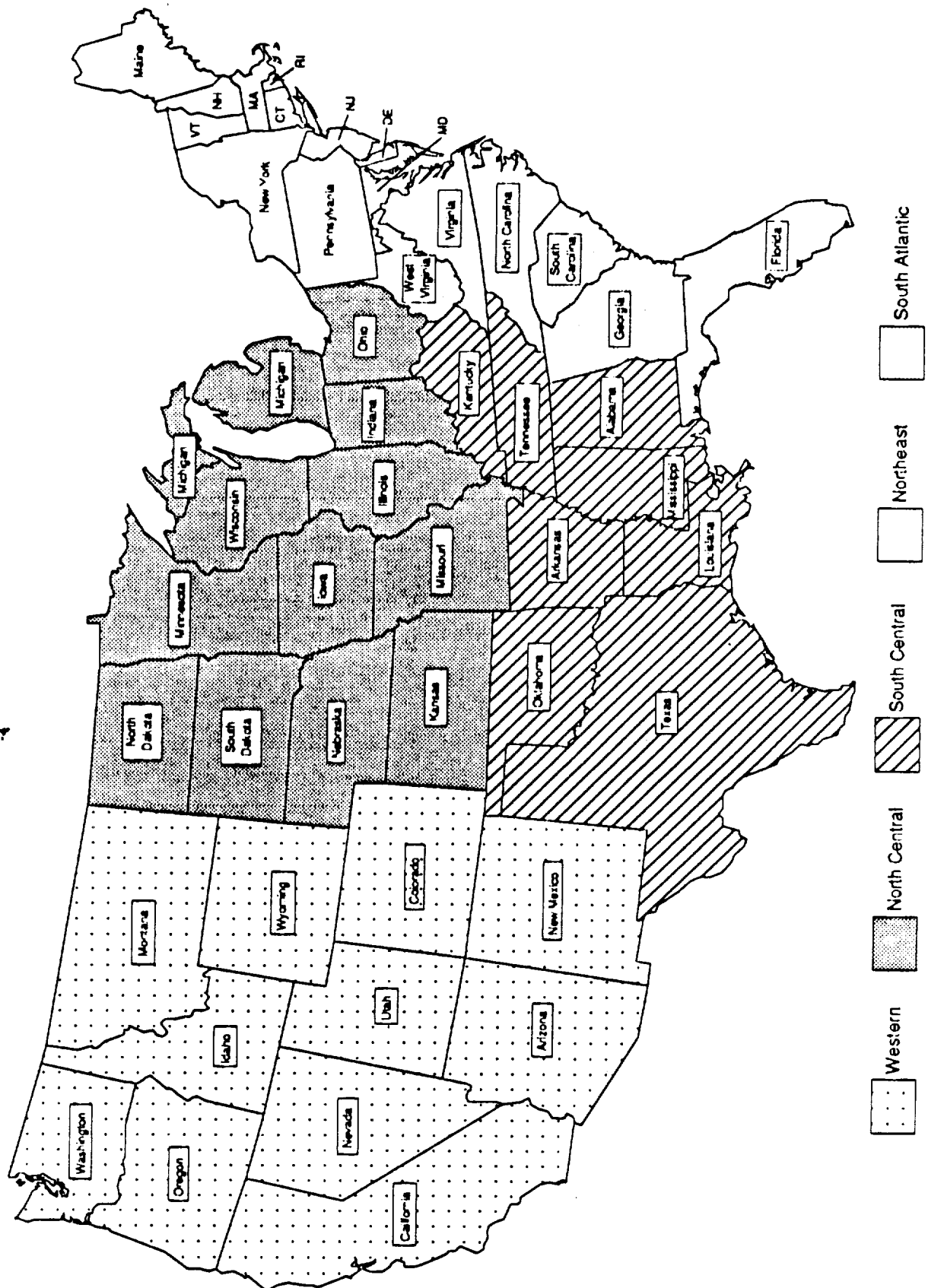
INTRODUCTION AND METHOD OF APPROACH

SRI International (SRI) is pleased to present this final report on liquid hydrogen production and demand, under contract NAS10-11643. Kennedy Space Center (KSC), the single largest purchaser of liquid hydrogen in the United States, manages liquid hydrogen in support of government programs. Increased demand from the commercial sector, as well as NASA's heavy reliance on hydrogen produced from a single hydrogen plant, has prompted KSC to evaluate current and anticipated hydrogen production and consumption in the government and commercial sectors, in order to determine the type of procurement best suited to meeting KSC's hydrogen requirements. The government analysis was conducted by KSC. This study represents SRI's assessment of the commercial sector.

To conduct this study, SRI compiled available information on hydrogen production, trade, consumption and macro-economic trends likely to affect consumption. This information was supplemented by extensive interviews with hydrogen producers, consumers and industry organizations. Specific objectives of the study are as follows:

- Identify liquid hydrogen producers in the United States and Canada during the 1980-1989 period, including:
 - Plant locations, capacities, date on stream and production process used (e.g., burning natural gas or liquefaction of by-product hydrogen)
 - True delivery capability assessed on a best-efforts basis.
- Compile information on expected changes in liquid hydrogen production capabilities in the United States and Canada over the 1990-2000 period.
- Describe how hydrogen is used in each consuming industry and estimate U.S. liquid hydrogen consumption for the chemicals, metals, electronics, fats and oil, and glass industries, and report data on a regional basis as illustrated in Figure ES-1.
- Estimate historical consumption for the years 1980, 1985, 1987, 1988, 1989, and future consumption for 1990, 1995, 2000.
- Assess the influence of international demands on U.S. plants, and in particular, the influence of the Canadian market on Canadian and U.S. production.

Figure ES-1
LIQUID HYDROGEN CONSUMING REGIONS



CONCLUSIONS

As a result of this survey, SRI can present the following observations about the producers of hydrogen, and some projections about the future use.

Liquid Hydrogen Producers

Four companies produce liquid hydrogen at 8 locations in North America. Three of the plants are located in Canada; five are in the United States. A history of producers, plants capacities for the 1980-1990 period is summarized in Table ES-1.

Significant changes that have taken place in terms of liquid hydrogen suppliers over the 1980-1990 period include the following:

- Idle capacity on the West Coast was closed or moved east in order to be closer to the market.
- U.S. based capacity decreased 6.8% while Canadian capacity increased from no capacity in 1980 to 50 tons per day by July 1990. Overall, this corresponds to a 27% increase in North American capacity.
- The number of companies producing liquid hydrogen has expanded. In 1980, Air Products, Airco, and Union Carbide all produced in the United States. In 1982, Airco ceased production and participated in the business as a distributor, leaving Air Products and Union Carbide as the sole producers over the 1983-1988 period. In 1988 the situation changed when HydrogenAL began operating its liquid hydrogen plant in Becancour, Quebec. In June 1990, Airco began operating a plant in Magog, Quebec. Product from HydrogenAL's plant is distributed in the United States by Liquid Air Corporation.
- The newer plants have tended to be smaller than previous plants and to use by-product hydrogen streams.

Industry is still adjusting to the Canadian capacity that has recently come on stream. No company has formally announced plans to construct a new liquid hydrogen plant in North America although there have been rumors of plants being considered for the South Atlantic and the West Coast. Air Products is in the process of debottlenecking its facilities, which will increase the company's North American nameplate capacity to 106-108 tons per day by 1992. No company has announced plans to close capacity, although it is reasonable to believe that Union Carbide will permanently close its Ashtabula plant and add capacity elsewhere by 1995.

Nameplate capacities for any given year are somewhat higher than true delivery capability on an annual basis when factors such as losses and downtime for plant maintenance are taken into account. In general, it is estimated that plants are able to have 92% of nameplate capacity available for delivery. One exception to this may be the Union Carbide plant at Ontario, CA, which is difficult to rate effectively since the plant operates well under capacity due to insufficient demand for product.

Table ES-1
NORTH AMERICAN LIQUID HYDROGEN PRODUCERS
Nameplate Capacity as of January 1 of the Given Year
(Short Tons per Day)

| Producing Company and Plant Location | Date on Stream | Production Process or Hydrogen Source | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991 | Remarks |
|--|----------------|--|------|------|------|------|------|------|------|------|------|------|------|------|---|
| United States | | | | | | | | | | | | | | | |
| Air Products and Chemicals Inc. Industrial Gases Division Long Beach, CA | 1963 | By-product refinery hydrogen purchased from Atlantic Richfield Company, Carson, CA | 30 | 30 | 15 | 15 | 15 | 15 | 15 | 0 | 0 | 0 | 0 | 0 | A 15 ton per day liquefier was moved from this location to Sarnia, Ontario in 1981. The remaining capacity was closed when Air Products opened its Sacramento facility. |
| New Orleans, LA | 1965 | Steam reforming of natural gas | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 32.5 | 32.5 | 32.5 | 32.5 | 32.5 | |
| | 1977 | Steam reforming of natural gas | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 32.5 | 32.5 | 32.5 | 32.5 | 32.5 | |
| Sacramento, CA | 1986 | Steam reforming of natural gas | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.6 | 5.6 | 5.6 | 5.6 | 5.6 | |
| Total, Air Products | | | 90 | 90 | 75 | 75 | 75 | 75 | 75 | 71 | 71 | 71 | 71 | 71 | By 1992, debottlenecking is anticipated to raise Air Products' total U.S. nameplate capacity by 6-8 tons per day. |
| The BOC Group, Inc. Arco Distributor Gases Division Arco Gases Division Piedmont, NJ | 1963 | Hydrogen was purchased from Sun Oil Chemical Company, which co-produces hydrogen and carbon monoxide by steam reforming of natural gas | 6 | 6 | 6 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Permanently closed. |
| 4 | | | | | | | | | | | | | | | |
| Union Carbide Corporation Linde Division Ashabula, OH | 1974, 1976 | Steam reforming of natural gas, PSA purification | 18.8 | 18.8 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | Plant operates as needed to supplement production from Niagara Falls. A portion of the product from this facility is marketed in gaseous form and not liquified. The facility was initially designed to be capable of producing 18 tons per day of hydrogen, although the actual production capacity was 7 tons per day in 1974. In 1977 the compressors, expanders, and purification unit were modified and a second steam reformer was added, bringing capacity to 18.8 tons per day. The original steam reformer was closed in 1984, bringing capacity to 12 tons per day. |
| Niagara Falls, NY | 1981 | By-product of chlorine sodium hydroxide production, cryogenic purification | 0 | 0 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 33 | 33 | Facility was built to be easily expanded by an additional 11 tons per day. By-product hydrogen is available from three sources: Occidental Chemical Corporation (with the capacity to generate 23 tons of by-product hydrogen per day), Nalco, Inc. (with the capacity to generate 16 tons of by-product hydrogen per day), and Olin Corporation (with the capacity to generate 6 tons of by-product hydrogen per day). Union Carbide is not the only consumer of hydrogen from these plants. |
| Ontario, CA | 1962 | Steam reforming of natural gas, PSA purification installed in 1984 | 32 | 32 | 32 | 32 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | A portion of the product produced from this facility is marketed in gaseous form and not liquified. |
| Total, Union Carbide | | | 51 | 51 | 66 | 66 | 55 | 55 | 55 | 55 | 55 | 55 | 60 | 66 | |

Table ES-1 (concluded)

| Producing Company and Plant Location | Date on Stream | Production Process or Hydrogen Source | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991P | Remarks |
|---|----------------|--|------|------|------|------|------|------|------|------|------|------|------|-------|--|
| Canada | | | | | | | | | | | | | | | |
| Air Products and Chemicals Inc. Sarnia, Ontario | 1982 | By-product hydrogen is purchased from Dow Chemical Canada Inc.'s chlorine-sodium hydroxide plant | 0 | 0 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 22 | 24 | 24 | Liquefier was moved to this location from Long Beach, CA in 1981. The facility was debottlenecked in 1985 and again in 1990. By 1992, capacity will be increased to 25 tons per day. Dow has the capacity to produce 25 tons per day of by-product hydrogen. |
| BOC Group, Inc. Airco Industrial Gases, Division Mississauga, Quebec | June 1990 | By-product hydrogen is purchased from Elxa Nobel Canada Inc.'s sodium chlorate plant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | Plant came on-stream June 1, 1990. Elxa Nobel Canada (formerly Quebeck, Inc.) has the capacity to produce 15 tons per day of hydrogen. |
| HydrogenAL Co. Ltd. (A joint venture between Hydro-Quebec and Canadian Liquid Air Ltd.) Beauceville, Quebec | 1988 | By-product hydrogen purchased from C-H-L Corporation's chlorine sodium hydroxide plant (8 tons per day) and electrolytic hydrogen (3 tons per day) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | 11 | 11 | Plant came on-stream in 1988. C-H-L has the capacity to produce 21 tons per day of by-product hydrogen. C-H-L also supplies by-product hydrogen to Orychem Canada's nearby hydrogen peroxide plant. A steam reformer operates nearby to supply gaseous hydrogen to Norsk Hydro Canada Inc. This hydrogen can reportedly be routed to HydrogenAL. |
| Total Canadian Nameplate Capacity | | | 0 | 0 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 33 | 35 | 54 | |
| Total North American Nameplate capacity | | | 147 | 147 | 162 | 162 | 145 | 145 | 145 | 141 | 141 | 159 | 172 | 191 | |

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Consumption

Although government use typically accounts for only about one fifth of all liquid hydrogen consumed in the United States, it is the only application that requires significant volumes of liquid hydrogen. For commercial consumers, liquid hydrogen is purchased for convenience or, particularly for small volume users, economics. The liquid hydrogen is then vaporized and used in gaseous form. This could change if a new market that consumed hydrogen in liquid form, such as fuel for commercial aircraft, emerged. SRI does not anticipate this occurring before 2000.

The primary commercial markets for liquid hydrogen are in the chemical, metals, electronics, fats and oils, and glass industries. Current, historic, and projected liquid hydrogen consumption for 1990 in each of these industries is presented in Table ES-2.

Table ES-2
U.S. COMMERCIAL MARKET FOR LIQUID HYDROGEN
(tons per day)

| | Chemicals, Petrochemicals, and Refining | Metals | Electronics | Fats and Oils | Glass | Other | Total |
|------|--|---------------|--------------------|--------------------------|--------------|--------------|--------------|
| 1980 | 18.2 | 14.7 | 14.6 | 7.6 | 4.9 | 1.1 | 61.0 |
| 1985 | 21.7 | 17.2 | 16.1 | 6.7 | 5.0 | 1.1 | 67.8 |
| 1987 | 23.5 | 18.6 | 16.7 | 6.4 | 5.1 | 2.4 | 72.8 |
| 1988 | 24.5 | 19.5 | 17.5 | 6.2 | 5.4 | 1.9 | 74.9 |
| 1989 | 30.1 | 20.5 | 18.3 | 6.5 | 5.4 | 2.7 | 83.5 |
| 1990 | 31.6 | 21.8 | 19.1 | 6.1 | 5.1 | 3.1 | 86.8 |
| 1995 | 37-38 | 30-32 | 24-25 | 8 | 6 | 4 | 109-113 |
| 2000 | 43-48 | 40-44 | 30-31 | 9-11 | 6-8 | 4-6 | 132-148 |

Source: SRI estimates

The commercial market for liquid hydrogen increased at an average annual rate of 2.1% from 1980 to 1985, and at an average annual rate of 3.4% from 1985 to 1988. Consumption increased a dramatic 11.5% in 1989 over the previous year. Reasons for the increase include real growth, efforts by new producers to load their current or planned plants, and temporary market opportunities. For example, when one consumer's source of by-product hydrogen went down for about eight months in 1989 and 1990, the consumer was forced to purchase liquid hydrogen. This single account represented up to 140,000 standard cubic feet per hour (0.36 tons per hour) of demand.

Industry representatives have divergent views regarding future commercial demand for liquid hydrogen, especially over the 1995-2000 period. Representatives have reported anticipated growth rates ranging from 4% to 10%.

SRI forecasts U.S. consumption of liquid hydrogen to increase 4% between 1989 and 1990, then grow at an average annual rate of approximately 4.5% to 5.5% for the next five years. This corresponds to growth at an average annual rate of 4.5% to 5.2% over the 1989 to 1995 period. Demand from 1995 to 2000 is forecast to increase at an average annual rate of 4.0% to 5.5%. Overall, demand is forecast to increase at an average annual rate of 4.3% to 5.3% from 1989 to 2000. SRI believes that growth will increase at the lower end of the range predicted by industry for the following reasons:

- A large part of growth in the industry has been through conversion of captive gaseous hydrogen producers to purchasers of liquid hydrogen. There are expected to be fewer opportunities for this sort of growth in the future.
- In response to increased competition in supplying liquid hydrogen, some gas companies appear to be converting large liquid hydrogen accounts to supplier owned, on-site plants, which are generally longer term contracts.
- As plant loadings increase, gas companies are likely to emphasize servicing more profitable accounts, causing some consumers to convert to captive production.
- Demand in 1989 was unusually high.

Geographically, consumption is concentrated northeast of the Mississippi river. This will continue to be the case through 2000. The following table displays where the major markets for liquid hydrogen are geographically.

Table ES-3
U.S. LIQUID HYDROGEN MARKETS IN 1989 BY GEOGRAPHIC REGION
(tons per day)

| | Northeast | North Central | South Atlantic | South Central | West | Total |
|---|-------------|------------------|----------------|------------------|-------------|-------------|
| Chemicals, petrochemicals, and refining | 8.4 | 7.6 | 5.0 | 7.6 | 1.5 | 30.1 |
| Metals | 7.8 | 7.1 | 1.8 | 2.4 | 1.4 | 20.5 |
| Electronics | 3.6 | 2.0 | 1.8 | 4.6 | 6.3 | 18.3 |
| Fats and oils | 0.8 | 2.9 | 1.0 | 1.3 | 0.5 | 6.5 |
| Glass | 0.6 | 1.6 | 1.2 | 1.3 | 0.7 | 5.4 |
| Other | 0.8 | 0.7 | 0.4 | 0.5 | 0.3 | 2.7 |
| Total | 22.0 | 21.9 | 11.2 | 17.7 | 10.7 | 83.5 |

International demand has placed and will continue to place insignificant demands on U.S. plants. It is expected that Canadian plants will continue to represent a significant source of liquid hydrogen to the commercial sector.

Canada is reviewing a large scale project to export liquid hydrogen as an energy carrier to Western Europe. Since it is highly uncertain whether the project will come to fruition before 2000, and since the project would include the construction of a new hydrogen plant close to a shipping terminal, it is assumed that offshore demands for Canadian hydrogen will be minimal.

INTRODUCTION

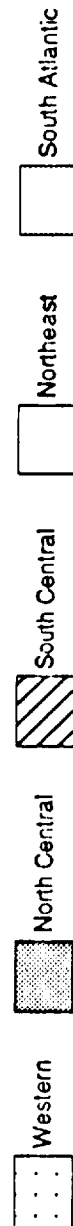
SRI International (SRI) is pleased to present this final report on liquid hydrogen production and demand, under contract NAS10-11643. Kennedy Space Center (KSC), the single largest purchaser of liquid hydrogen in the United States, manages liquid hydrogen in support of government programs. The first liquid hydrogen plants in the United States were built primarily to supply government contracts for liquid hydrogen. With the increased availability of liquid hydrogen, however, producers began to identify accounts in the commercial sector that would benefit from purchasing product in liquid form. Increased demand from the commercial sector, as well as NASA's heavy reliance on hydrogen produced from a single hydrogen plant, has prompted KSC to evaluate current and anticipated hydrogen production and consumption in the government and commercial sectors, in order to determine the type of procurement best suited to meeting KSC's hydrogen requirements. The government analysis was conducted by KSC. This study represents SRI's assessment of the commercial sector.

To conduct this study, SRI compiled available information on hydrogen production, trade, consumption and macro-economic trends likely to affect consumption. This information was supplemented by extensive interviews with hydrogen producers, consumers and industry organizations. Specific objectives of the study are as follows:

- Identify liquid hydrogen producers in the United States and Canada during the 1980-1989 period, including:
 - Plant locations, capacities, date on stream and production process used (e.g., burning natural gas or liquefaction of by-product hydrogen)
 - True delivery capability assessed on a best-efforts basis.
- Compile information on expected changes in liquid hydrogen production capabilities in the United States and Canada over the 1990-2000 period.
- Describe how hydrogen is used in each consuming industry and estimate U.S. liquid hydrogen consumption for the chemicals, metals, electronics, fats and oil, and glass industries, and report data on a regional basis as illustrated in Figure 1.
- Estimate historical consumption for the years 1980, 1985, 1987, 1988, 1989, and future consumption for 1990, 1995, 2000.
- Assess the influence of international demands on U.S. plants, and in particular, the influence of the Canadian market on Canadian and U.S. production.

The remainder of this report discusses the current producers and consumers of liquid hydrogen, and suggests trends in consumption for the chemicals, metals, and electronics industries.

2



LIQUID HYDROGEN PRODUCERS

In 1980 three companies, Air Products and Chemicals, Inc. (Air Products), the Linde division of Union Carbide Corporation (Union Carbide), and Airco Inc. (Airco, later acquired by BOC Group, Inc.), produced liquid hydrogen in North America. All of the plants were located in the United States. The hydrogen liquified at each of these facilities was hydrocarbon based.

Over the 1980-1985 period, several changes occurred. Air Products and Union Carbide built new plants that took advantage of by-product hydrogen streams in areas with comparatively inexpensive electricity. Airco decided it was not economic to continue to operate its plant but continued to participate in the liquid hydrogen business as a distributor. This left Air Products and Union Carbide as the only North American producers over the 1983-1988 period.

Industry observers perceived the liquid hydrogen business to be profitable. This factor, combined with Canada's interest in utilizing its relatively inexpensive and abundant supplies of electricity, provided the right background for L'Air Liquide and BOC Group to enter the liquid hydrogen business in North America. In 1988 HydrogenAL Co. Ltd., a joint venture between Hydro-Quebec and Canadian Liquid Air (owned by L'Air Liquide SA, France), began operating a liquid hydrogen plant in Becancour, Quebec. On June 1, 1990, Airco (owned by BOC Group) began operating a plant in Magog, Quebec. Table 1 identifies plant locations, capacities, dates on stream, and production processes for liquid hydrogen producers in the United States and Canada during the 1980-1991 period.

True delivery capability is somewhat lower than the nameplate capacity. Factors that are sometimes quoted for converting nameplate capacity to true delivery capability include an on-stream factor (the days per year the plant operates) and a utilization factor (the ratio of product leaving the plant to product produced, which accounts for the losses associated with storing and handling the product before it leaves the plant). Historically, industry observers have estimated true production capacity at about 85% of nameplate capacity. In 1990, it is estimated that all plants are able to produce 92% of nameplate capacity. Air Products is believed to rate its plants closer to their delivery capabilities and may be able to produce at capacity on a short-term basis. Additional product losses take place in delivering the product to the customer. Delivery losses will vary depending on a supplier's delivery system and the number of tanks that must be filled at a customer site. In general, delivery losses are minor, estimated at 2 to 3%.

Not all of the North American plants are currently operating at capacity. The two new Canadian plants in Quebec, Magog and Becancour, are estimated to be running at about 50% capacity. In the United States, the Union Carbide facility at Ashtabula, OH, is run as needed to supplement production from Niagara Falls. Union Carbide's plant at Ontario, CA, is also not fully loaded. Although officially rated at 21-22 tons per day, the Ontario, CA facility is not believed to be ready to produce that amount on demand; industry sources estimate that 17 tons per day may be a more realistic nameplate capacity without modification to the plant or changes in operating procedures. The Ashtabula and Ontario facilities are currently marketing a portion of the gas stream available for liquefaction as gaseous hydrogen.

Table 1
NORTH AMERICAN LIQUID HYDROGEN PRODUCERS
Nameplate Capacity as of January 1 of the Given Year
(Short Tons per Day)

| Producing Company and Plant Location | Date on Stream | Production Process or Hydrogen Source | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991p | Remarks |
|---|----------------|--|------|------|------|------|------|------|------|------|------|------|------|-------|--|
| United States | | | | | | | | | | | | | | | |
| Air Products and Chemicals Inc. Industrial Gases Division Long Beach, CA | 1963 | By-product refinery hydrogen purchased from Atlantic Richfield Company, Carson, CA | 30 | 30 | 15 | 15 | 15 | 15 | 15 | 0 | 0 | 0 | 0 | 0 | A 15 ton per day liquefier was moved from this location to Samia, Ontario in 1981. The remaining capacity was closed when Air Products opened its Sacramento facility |
| | 1965 | Steam reforming of natural gas | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 32.5 | 32.5 | 32.5 | 32.5 | 32.5 | |
| | 1977 | Steam reforming of natural gas | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 32.5 | 32.5 | 32.5 | 32.5 | 32.5 | |
| | 1986 | Steam reforming of natural gas | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.6 | 5.6 | 5.6 | 5.6 | 5.6 | |
| Total Air Products | | | 90 | 90 | 75 | 75 | 75 | 75 | 75 | 71 | 71 | 71 | 71 | 71 | By 1992, debottlenecking is anticipated to raise Air Products' total U.S. nameplate capacity by 6.6 tons per day |
| The SOC Group, Inc. Airco Distributor Gases Division Airco Gases Division Piedmont, NJ | | | | | | | | | | | | | | | |
| | 1963 | Hydrogen was purchased from Sun Oil Chemical Company, which co-produces hydrogen and carbon monoxide by steam reforming of natural gas | 6 | 6 | 6 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Permanently closed |
| Union Carbide Corporation Linde Division Ashabula, OH | | | | | | | | | | | | | | | |
| | 1974, 1976 | Steam reforming of natural gas, PSA purification | 18.8 | 18.8 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | Plant operates as needed to supplement production from Niagara Falls. A portion of the product from this facility is marketed in gaseous form and not liquified. The facility was initially designed to be capable of producing 18 tons per day of hydrogen, although the actual production capacity was 7 tons per day in 1974. In 1977 the compressors, expanders, and purification unit were modified and a second steam reformer was added, bringing capacity to 18.8 tons per day. The original steam reformer was closed in 1984, bringing capacity to 12 tons per day |
| Niagara Falls, NY | | | | | | | | | | | | | | | |
| | 1981 | By-product of chlorine sodium hydroxide production, cryogenic purification | 0 | 0 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 22 | 33 | 33 | Facility was built to be easily expanded by an additional 11 tons per day. By-product hydrogen is available from three sources: Occidental Chemical Corporation (with the capacity to generate 23 tons of by-product hydrogen per day), Niagara Inc. (with the capacity to generate 16 tons of by-product hydrogen per day), and Olin Corporation (with the capacity to generate 6 tons of by-product hydrogen per day). Union Carbide is not the only consumer of hydrogen from these plants |
| Ontario, CA | | | | | | | | | | | | | | | |
| | 1962 | Steam reforming of natural gas, PSA purification installed in 1964 | 32 | 32 | 32 | 32 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | A portion of the product produced from this facility is marketed in gaseous form and not liquified |
| Total Union Carbide | | | 51 | 51 | 66 | 66 | 55 | 55 | 55 | 55 | 55 | 55 | 66 | 66 | |

Table 1 (concluded)

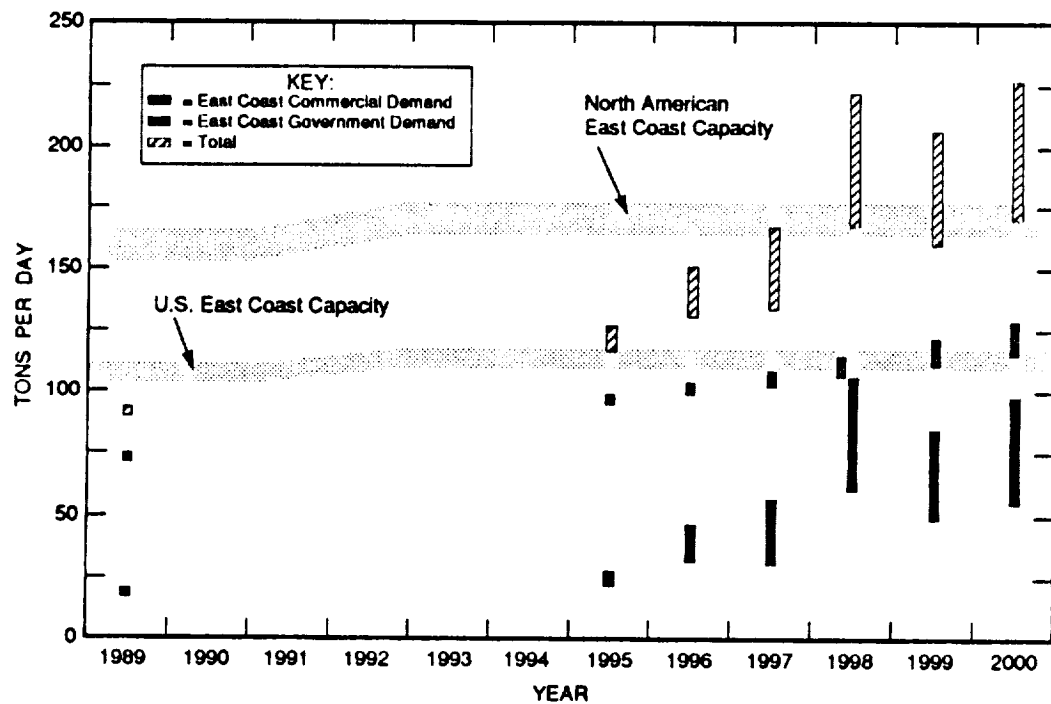
| Producing Company and Plant Location | Date on Stream | Production Process or Hydrogen Source | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 | 1987 | 1988 | 1989 | 1990 | 1991P | Remarks |
|---|----------------|---|------|------|------|------|------|------|------|------|------|------|------|-------|--|
| Canada | | | | | | | | | | | | | | | |
| Air Products and Chemicals Inc. Sarnia, Ontario | 1982 | By-product hydrogen is purchased from Dow Chemical Canada Inc.'s chlorine sodium hydroxide plant | 0 | 0 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 22 | 24 | 24 | Liquefier was moved to this location from Long Beach, CA in 1981. The facility was debottlenecked in 1989 and again in 1990. By 1992, capacity will be increased to 25 tons per day. Dow has the capacity to produce 25 tons per day of by-product hydrogen. |
| BOC Group Inc. Airco Industrial Gases, Division Mississauga, Quebec | June 1990 | By-product hydrogen is purchased from Elxa Nobel Canada Inc.'s sodium chlorate plant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | Plant came on-stream June 1, 1990. Elxa Nobel Canada (formerly Querford, Inc.) has the capacity to produce 19 tons per day of hydrogen. |
| HydrogenAL Co. Ltd. (A joint venture between Hydro-Quebec and Canadian Liquid Air Ltd.) Becancour, Quebec | 1988 | By-product hydrogen purchased from C-I-L Corporation's chlorine sodium hydroxide plant (8 tons per day); and electrolytic hydrogen (3 tons per day) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | 11 | 11 | Plant came on-stream in 1988. CIL has the capacity to produce 21 short tons per day of by-product hydrogen. CIL also supplies by-product hydrogen to Oxychem Canada's nearby hydrogen peroxide plant. A steam reformer operates nearby to supply gaseous hydrogen to Norsk Hydro Canada Inc. This hydrogen can reportedly be routed to HydrogenAL. |
| Total Canadian Nameplate Capacity | | | 0 | 0 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 33 | 35 | 54 | |
| Total North American Nameplate capacity | | | 147 | 147 | 162 | 162 | 145 | 145 | 145 | 141 | 141 | 159 | 172 | 191 | |

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Industry is still adjusting to the Canadian capacity that has recently come on stream. No company has formally announced plans to construct a new liquid hydrogen plant in North America although there have been rumors of plants being considered for the South Atlantic and the West Coast. Air Products is currently conducting a debottlenecking program that will increase total company capacity by 12 to 14 tons per day in terms of nameplate capacity, or 11 to 12 tons in terms of actual production capability, by 1992 as compared to 1990.

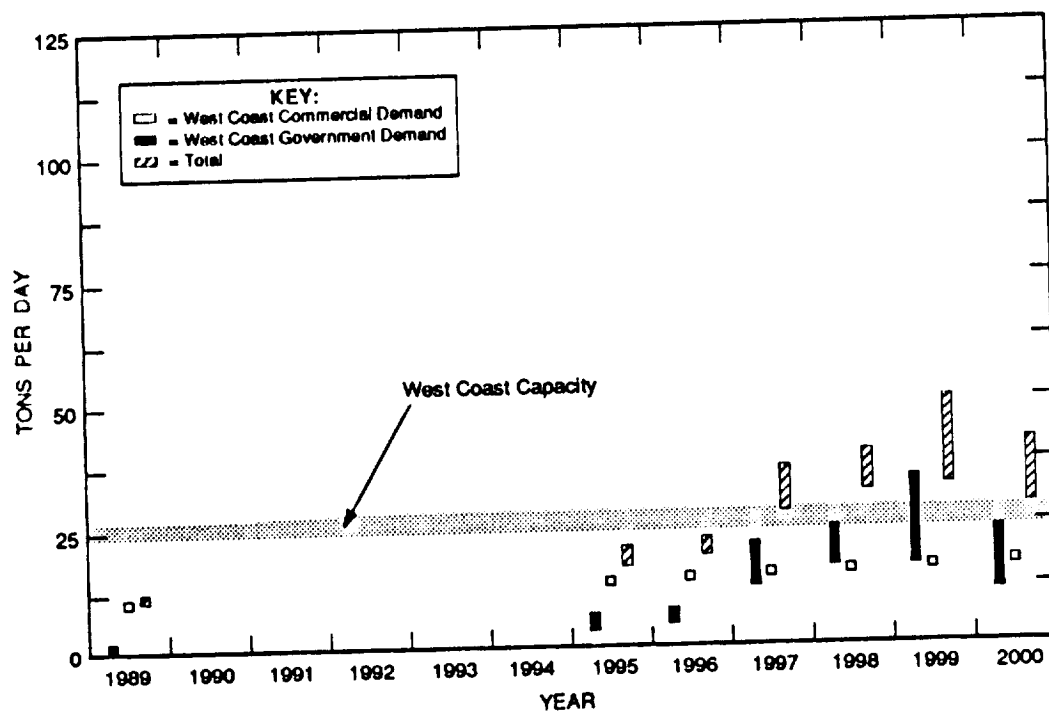
Despite the presence of excess capacity there have been times when extraordinary circumstances have caused supplies to be short, for example, in late May of 1990, Air Products' Sarnia plant was down for scheduled maintenance. Meanwhile, a strike curtailed deliveries from the plants in Quebec, and Union Carbide's Ashtabula plant was down temporarily from fouling of the catalyst. These supply problems, combined with a period of high demand for the space program, caused a temporary problem in meeting demand despite the theoretical excess of capacity as compared to demand. North American capacity is compared to current and future liquid hydrogen demand as projected by SRI in Figures 2, 3, and 4. Figure 4 also shows how SRI's projections compare to more optimistic forecasts.

Figure 2
EAST COAST LIQUID HYDROGEN PROJECTION



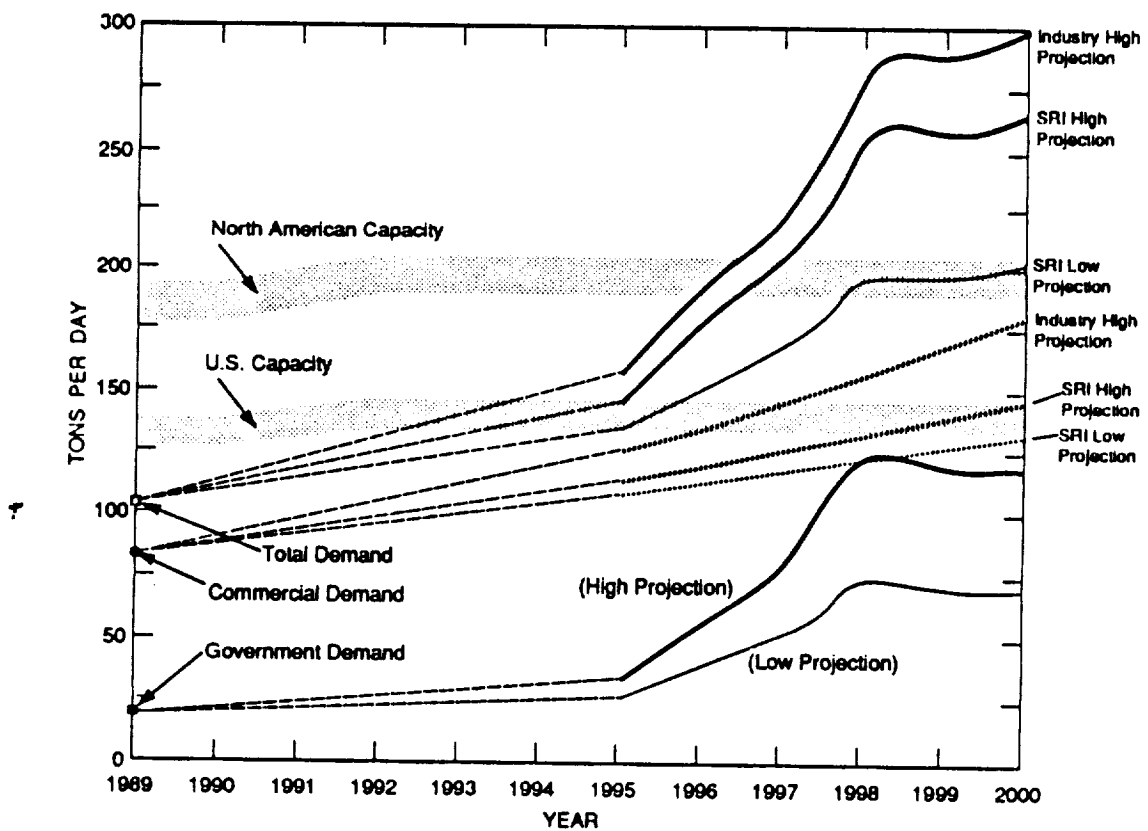
SOURCES: NASA (government demand) and SRI International (all other data).

Figure 3
WEST COAST LIQUID HYDROGEN PROJECTION



SOURCES: NASA (government demand) and SRI International (all other data).

Figure 4
TOTAL U.S. LIQUID HYDROGEN PROJECTION



SOURCES: NASA (government demand) and SRI International (all other data).

LIQUID HYDROGEN CONSUMPTION

MARKET OVERVIEW

In 1989, an estimated 2,390 billion cubic feet of intentionally produced hydrogen were consumed in the U.S. This figure includes by-product hydrogen intentionally recovered for merchant use, but excludes by-product hydrogen used as fuel or vented, and also excludes large volumes of by-product hydrogen that are produced and consumed captively by refineries. Of the 2,390 billion cubic feet consumed, an estimated 2,324 billion cubic feet were produced captively and consumed in gaseous form primarily by the ammonia, methanol, and petroleum refining industries. Of the remaining 66 billion cubic feet of hydrogen, representing merchant product, an estimated 11.7 billion cubic feet were consumed in liquid form. This is illustrated in Table 2, following, with figures based on SRI estimates. The petroleum refineries consumption does not include hydrogen produced as a by-product of catalytic reforming.

Table 2
U.S. CONSUMPTION OF HYDROGEN-1989

| | Billions of Cubic Feet | Tons per Day |
|-----------------------------|---------------------------|-----------------|
| Ammonia Producers | 1,147 | 8,180 |
| Refineries ^a | 895 | 6,390 |
| Methanol Producers | 172 | 1,230 |
| Small-Volume Captive Users | 110 | 785 |
| Small-Volume Merchant Users | 54 (gas) | 385 (gas) |
| | 12 (liquid) | 84 (liquid) |
| Total^b | 2,390 | 17,054 |

a. Datum represents hydrogen capacity installed at refineries and does not include hydrogen produced as a by-product of catalytic reforming. In 1989, catalytic reforming generated an estimated 1.4-1.7 trillion cubic feet of hydrogen.

b. In addition to hydrogen that is produced or recovered for consumption, large volumes of by-product hydrogen are generated and used as fuel or vented.

Source: SRI estimates.

In the commercial sector, there are currently no large volume uses that require liquid hydrogen. Liquid hydrogen has achieved widespread use because of the savings in transportation

and handling costs for the liquid form compared to the gaseous form for consumers who find it is not economic or otherwise feasible to produce hydrogen captively or purchase it via pipeline.

Some industries that use gaseous hydrogen will be more inclined to purchase it in liquid form than others. For example, applications that need extremely high purity hydrogen will generally prefer to use liquid hydrogen because the process of liquefaction produces an extremely pure product. Thus, the electronics industry has historically tended to use liquid hydrogen.

For the remaining industries—chemicals, metals, fats and oils, and glass—the decision to use liquid hydrogen is primarily based on an individual company's proximity to a source of gaseous hydrogen and the volumes of hydrogen consumed. For distances beyond 100 miles from the source, liquid hydrogen can typically be delivered more economically than gas unless the gaseous hydrogen can be delivered by pipeline. In general, bulk gas and bulk liquid hydrogen costs are roughly the same for consumers purchasing 40 to 50 thousand standard cubic feet of product per month. For larger purchases, gas is generally more expensive on a cost-per-unit basis. However, with liquid hydrogen there are losses due to evaporation. For this reason, liquid hydrogen is generally not recommended for locations where less than 100,000 cubic feet per month are consumed.

When a company's requirements are large enough, it becomes economic to have the hydrogen produced at the consuming location. These plants are called captive plants if owned by the consumer and on-site plants if owned and operated by an industrial gas company. Although on-site hydrogen production costs can vary considerably depending on the price of the feedstock, industry sources state that liquid hydrogen and on-site hydrogen costs are usually equivalent for locations that consume 8 to 10 million cubic feet per month. If consumption is greater, on-site hydrogen is generally less expensive than liquid. This does not necessarily mean that all users of over 10 million cubic feet will have an on-site plant installed. Companies with borderline consumption are often willing to pay a bit more for liquid hydrogen for the following reasons:

- If a company's hydrogen requirements change, the company is not saddled with a plant that it may no longer need.
- The company does not need to worry about plant maintenance or the reliability of its hydrogen supply.
- Liquid hydrogen may be purchased in direct accordance with a company's requirements if use rates are not continuous.

Companies with captive facilities may also purchase liquid hydrogen on occasion. For example, liquid hydrogen may be purchased when the hydrogen plant is closed for scheduled maintenance periods, if the hydrogen plant is not operating properly, or to supplement captive hydrogen during periods of peak demand. Captive plants typically close for maintenance once a year.

No changes in production technology that will significantly alter the economics of captive production are anticipated by industry. However, it is unclear at this time what impact gas separation membranes will have on the merchant hydrogen business. Membranes can be used to clean up a by-product hydrogen stream, displacing demand for generated or purchased hydrogen. Membranes can only be used to concentrate hydrogen, not to produce hydrogen.

In the chemicals, metals, and fats and oils industries, hydrogen is supplied by captive production, purchased gas, and purchased liquid. In the glass industry, all of the users currently purchase liquid hydrogen.

Liquid hydrogen consumption in a given region can vary by large amounts on short notice, particularly in the chemical, petrochemical and refining industries where a large portion of consumption is for servicing accounts that ordinarily have an alternate hydrogen source available. Consumption can decrease dramatically when a company that has been consuming liquid hydrogen decides it would be more economic to have a plant on site.

The commercial market for liquid hydrogen increased at an average annual rate of 2.1% from 1980 to 1985, and at an average annual rate of 3.4% from 1985 to 1988. Consumption increased a dramatic 11.5% in 1989 over the previous year. Reasons for the increase include real growth, efforts by new producers to load their current or planned plants, and temporary market opportunities. Current, historic, and projected liquid hydrogen consumption in each of the major consuming industries is presented in Table 3.

Table 3
U.S. COMMERCIAL MARKET FOR LIQUID HYDROGEN
(millions of cubic feet)

| | Chemicals, Petrochemicals, and Refineries | Metals | Electronics | Fats and Oils | Glass | Other | Total |
|------|--|-----------------|--------------------|--------------------------|---------------|--------------|-------------------|
| 1980 | 2,555 | 2,050 | 2,040 | 1,060 | 685 | 160 | 8,550 |
| 1985 | 3,040 | 2,410 | 2,250 | 940 | 700 | 160 | 9,500 |
| 1987 | 3,300 | 2,600 | 2,340 | 900 | 720 | 340 | 10,200 |
| 1988 | 3,430 | 2,730 | 2,455 | 870 | 750 | 265 | 10,500 |
| 1989 | 4,215 | 2,870 | 2,565 | 910 | 760 | 380 | 11,700 |
| 1990 | 4,430 | 3,050 | 2,680 | 870 | 710 | 425 | 12,165 |
| 1995 | 5,210- 5,370 | 4,295- 4,440 | 3,340- 3,440 | 1,085- 1,185 | 795- 910 | 495- 515 | 15,220- 15,860 |
| 2000 | 6,035- 6,695 | 5,600- 6,240 | 4,160- 4,395 | 1,290- 1,480 | 855- 1,055 | 600- 830 | 18,540- 20,695 |

Industry representatives have divergent views regarding future commercial demand for liquid hydrogen, especially over the 1995-2000 period. Representatives have reported anticipated growth rates ranging from 4% to 10%.

SRI forecasts U.S. consumption of liquid hydrogen to increase at an average annual rate of 4.5% to 5.2% from 1989 to 1995. Demand from 1995 to 2000 is forecast to increase at an average annual rate of 4.0% to 5.5%. Overall, demand is forecast to increase at an average rate of 4.3% to 5.3% from 1989 to 2000.

SRI believes that growth will increase at the lower end of the range predicted by industry for the following reasons:

- A large part of past growth in the industry has been through conversion of captive gaseous hydrogen producers to purchasers of liquid hydrogen. There are expected to be fewer opportunities for this sort of growth in the future.
- In response to increased competition in supplying liquid hydrogen, some gas companies have been converting liquid hydrogen accounts to supplier owned on-site plants, which are generally longer term contracts. Examples include a Union Carbide facility that went on stream in 1989 to supply AT&T's fiber optics plant in Norcross, GA; Air Product's facility to supply FMC Corporation's chemical plant at South Charleston, WV; and Air Product's facility at American Cyanamid's chemical plant in Hannibal, MO
- As plant loadings increase, gas companies are likely to emphasize servicing more profitable accounts, causing some consumers to convert to captive production.
- Demand in 1989 was unusually high.

Geographically, consumption is concentrated in the northeastern states, Michigan, Indiana, and Ohio. This will continue to be the case through 2000. The following tables display data on the major markets for liquid hydrogen by market sectors.

CHEMICALS, PETROCHEMICALS, AND REFINERIES

Table 4 displays consumption in the chemical industry to date, and projections for the next ten years.

Table 4
LIQUID HYDROGEN CONSUMPTION IN THE CHEMICAL, PETROCHEMICAL, AND REFINING INDUSTRIES

| Year | Millions of Cubic Feet | Average Annual Growth |
|-------------|-------------------------------|------------------------------|
| 1980 | 2555 | |
| 1985 | 3040 | 3.5% (1980-1985) |
| 1987 | 3300 | |
| 1988 | 3430 | |
| 1989 | 4215 | 8.5% (1985-1989) |
| 1990 | 4430 | |
| 1995 | 5210-5370 | 3.6% to 4.1% (1989-1995) |
| 2000 | 6035-6695 | 3.0% to 4.5% (1995-2000) |

Chemical, Petrochemical, and Refining Applications

Hydrogen, a reducing agent, is widely used in the chemical, petrochemical, and refining industries. In addition to use for its chemical properties, hydrogen is used for cooling during the liquefaction of argon. Chemicals that consume hydrogen in their manufacture are listed in Table 5.

Table 5
HYDROGEN CONSUMING CHEMICALS AND PETROCHEMICALS

| | |
|-----------------------------|---|
| acrylamide | hydrogen peroxide |
| adiponitrile | hydrogenated bisphenol A |
| alcohols | hydrogenated rosin |
| p-aminophenol | hydrogenated styrene-butadiene block co-polymer |
| ammonia | hydrogenated terpene derivatives |
| aniline (from nitrobenzene) | isobutane |
| argon (liquid) | isopentane |
| ascorbic acid | isophorone diisocyanate |
| 1,4-butanediol | lithium hydride |
| butene-1 | methanol |
| butyrolactam | methylene di-para-phenylene isocyanate (MDI) |
| butyrolactone | pharmaceuticals |
| calcium hydride | piperidine |
| caprolactam | poly alpha-olefins |
| cyclohexane (from benzene) | polybutene-1 |
| cyclohexanol | polyethylene |
| cyclohexanone | polypropylene |
| cyclohexylamine | propylene oxide |
| ethyleneamines | resins |
| p-ethyltoluene | sodium hydride |
| fatty acids | sorbitol |
| furfuryl alcohol | terephthalic acid |
| hexamethylenediamine | tetrahydrofuran |
| hydrochloric acid | tetrahydrofurfuryl alcohol |
| hydrogen bromide | toluenediamine |

In the refining industry, hydrogen is primarily consumed in hydrotreating and hydrocracking.

Hydrogen Sources for Chemical, Petrochemical, and Refining Uses

The majority of hydrogen consumed in the chemical, petrochemical, and refining industries is gaseous hydrogen produced and consumed captively or supplied by pipeline. Hydrogen for this industry sector can be purchased, produced, or recovered.

Regional Consumption

The chemical, petrochemical, and refining industries are concentrated in the Northeast, North Central and South Central regions.

Trends in Consumption for Chemical, Petrochemical, and Refining Uses

This industry sector grew more rapidly than any other from 1985 to 1989, with consumption increasing almost 39%, which corresponds to growth at an average annual rate of 8.5%. This high rate of growth was the result of temporary market opportunities as well as real growth.

Short term, large volume accounts are particularly common in this industry sector. In 1989, there occurred some unusual short term demands for liquid hydrogen. For example, because of an explosion at a by-product producer's plant, a large consumer of by-product hydrogen was forced to purchase liquid hydrogen over an eight month period. This account alone could consume an estimated eight tons per day of product. Another large volume opportunity emerged in response to increased aniline demand which resulted in some companies purchasing liquid hydrogen to supplement captive hydrogen production.

Hydrogen consumption in all forms is expected to increase dramatically in this industry sector over the next ten years, particularly in the refining industry. However, the majority of the growth will be met with gaseous hydrogen produced captively. In the refining industry, increasing quantities of hydrogen will be required because of increased demand for products produced by hydrocracking, the use of increasingly heavy and sour crudes, and increased environmental restrictions. Hydrogen's ability to react with elements such as sulfur and the halogens is likely to lead to new uses in industries where the emission of these elements is or will be restricted.

Growth in this industry sector is particularly difficult to estimate because the sector is composed of many applications which will grow at widely varying rates and because this industry sector has the widest variety of options available to it for obtaining hydrogen. SRI forecasts liquid hydrogen consumption in this industry sector to increase at an average annual rate of 3.6% to 4.1% over the 1989-1995 period. Over the 1995-2000 period, consumption is expected to increase at an average annual rate of 3.0% to 4.5%. The lower end of this range assumes that the rate of growth in hydrogen consumption will slow as is projected for the chemical industry generally. The higher end of the range assumes increased liquid hydrogen consumption primarily for environmental applications.

METALS

Table 6 displays hydrogen consumption in the metals industry, and projected consumption for the next ten years.

Table 6
LIQUID HYDROGEN CONSUMPTION IN METALS

| Year | Millions of Cubic Feet | Average Annual Growth |
|-------------|-----------------------------------|----------------------------------|
| 1980 | 2,050 | |
| 1985 | 2,410 | 3.3% (1980-1985) |
| 1987 | 2,600 | |
| 1988 | 2,730 | |
| 1989 | 2,870 | 4.5% (1985-1989) |
| 1990 | 3,050 | |
| 1995 | 4,295-4440 | 7.0% to 7.5% (1989-1995) |
| 2000 | 5,600-6,240 | 5.5% to 7.0% (1995-2000) |

Metal Applications

In the metals sector, liquid hydrogen is used in both primary metal production and secondary metal processing. Primary operations that consume hydrogen include tungsten, tungsten carbide and molybdenum metal powder production. Secondary operations that consume hydrogen include heat treating, sintering, and brazing. The majority of hydrogen used in the metals industry is for secondary operations rather than primary metal production.

In tungsten and molybdenum metal powder production, hydrogen acts as a reducing agent, to reduce a tungsten or molybdenum oxide to its elemental form. In tungsten carbide production, hydrogen reacts with a hydrocarbon atmosphere generated by the reaction of carbon black and hydrogen to form tungsten carbide powder.

In secondary operations, hydrogen is commonly used as an atmosphere in furnaces that require an atmosphere for reduction or to improve the thermal conductivity of the atmosphere. Small quantities of hydrogen are sometimes used as a backfill gas in vacuum furnaces. Hydrogen is used in large quantities for heat treating; specific heat treating operations that consume hydrogen include normalizing low carbon steel prior to galvanizing, annealing of steel strip and coil, bright annealing of stainless steel, and decarburizing. Types of companies likely to consume hydrogen for heat treating include steel works, finishing mills, and in-house and commercial heat treaters.

Sintering is the process by which loose or compressed powders are bonded by heating at temperatures below the melting points of the major constituents. Because powdered metals undergoing sintering have such a large exposed surface area, hydrogen atmospheres are commonly used to prevent oxidation. Metal compacts that are typically sintered in a hydrogen atmosphere include tool steel, stainless steel, and nickel- and cobalt-base alloys.

Brazing is a technique used largely in the aerospace and electronics industries to join parts. Brazing joins solid materials together by heating them to a suitable temperature and by using a filler metal having a liquidus above 840 degrees Fahrenheit and below the solidus of the base materials.

Hydrogen Sources for Metals Uses

Hydrogen for primary metal production is typically purchased in liquid form or produced captively by steam reforming of natural gas. In secondary operations, a hydrogen atmosphere can be obtained in a variety of ways, including generation from natural gas (endothermic or exothermic atmospheres), dissociation of ammonia or methanol, and purchased hydrogen atmospheres. The largest volume consumers, such as large steel producers, may be located on a pipeline.

Companies that make powdered metal parts have traditionally dissociated ammonia to generate a hydrogen containing atmosphere. At in-house or commercial heat treating operations, generated hydrogen atmospheres have been traditional. Industrial gas companies have targeted powdered metal parts producers and heat treaters as potential liquid hydrogen markets and have been quite successful at persuading many hydrogen users to convert to purchased atmospheres.

Regional Consumption

Consumption in this industry is concentrated in the Northeast and North Central states. The steel industry is primarily located in the north central states, with a large concentration also in the Northeast. Many of the accounts in the North Central region are supplied with pipeline hydrogen. Heat treating operations are more broadly distributed geographically, but tend to be more common in regions with more equipment manufacturing, such as the Northeast and North Central regions. The largest number of powdered metal manufacturers can be found in Pennsylvania. Ranked next in quantity are Michigan, Illinois, California, Ohio and Massachusetts. Primary metal producers that purchase liquid hydrogen are almost all located in the Northeast.

Factors Affecting Consumption for Metals Uses

Liquid hydrogen consumption in the metals industry is expected to increase at an average annual rate of 7.0% to 7.5% from 1989 to 1995. This high rate of growth will be sustained by continued conversion from generated atmospheres to purchased atmospheres, high growth in the powdered metals industry, and higher concentrations of hydrogen being used in bell annealers in the steel industry.

From 1995 to 2000, the average annual rate of growth is expected to slow to 5.5% to 7.0%, to reflect the decrease in opportunities for conversion to purchased atmospheres or high hydrogen atmospheres.

ELECTRONICS

Table 7 displays hydrogen consumption in the electronics industry and projections for the next ten years.

Table 7
LIQUID HYDROGEN CONSUMPTION IN ELECTRONICS

| Year | Millions of Cubic Feet | Average Annual Growth |
|-------------|-----------------------------------|----------------------------------|
| 1980 | 2,040 | |
| 1985 | 2,250 | 2.0% (1980-1985) |
| 1987 | 2,340 | |
| 1988 | 2,455 | |
| 1989 | 2,565 | 3.3% (1985-1989) |
| 1990 | 2,680 | |
| 1995 | 3,340-3440 | 4.5% to 5.0% (1989-1995) |
| 2000 | 4,160-4395 | 4.5% to 5.0% (1995-2000) |

Electronic Applications

The largest volumes of hydrogen used in the electronics industry are used in integrated circuit (IC) manufacture. Other segments of the electronics industry that consume hydrogen include semiconductor grade polycrystalline silicon manufacture via the Siemens process, optical fibers manufacture for communications, and fused quartz manufacture.

Specific applications that use hydrogen in wafer fabrication (integrated circuit manufacture) are presented in Table 8. The largest volumes of hydrogen are believed to be used in epitaxy, where the reactive gases dichlorosilane and hydrogen chloride are diluted with hydrogen, which functions as both the reactive gas and carrier gas. Epitaxy is common to all integrated circuit manufacturing processes. Chemical vapor deposition of compound semiconductors such as gallium arsenide also consumes significant volumes of hydrogen; however, this industry is currently a small fraction of the silicon industry as a whole.

The remaining uses of hydrogen in wafer fabrication are comparatively minor. Ion implantation, for example, is a high vacuum process using little material. Oxidation involving pyrogenic steam generation is growing in popularity, but is only one of a number of processes that can be used. In diffusion annealing and bonding operations, hydrogen is a minor component mixed with nitrogen and argon to inhibit oxidation in carrier gases used. Hydrogen is a minor etchant and is primarily used with halogenated solvents to produce the etchants anhydrous hydrogen chloride and hydrogen fluoride on site.

In polysilicon production, silicon is produced by the pyrolytic decomposition of trichlorosilane or silicon tetrachloride. Hydrogen is also consumed as an atmosphere when growing single crystals from a melt of polycrystalline starting material. In the fabrication of optical fibers and quartz chambers and fixtures, hydrogen is used as a clean burning fuel.

Table 8
APPLICATIONS FOR HIGH-PURITY HYDROGEN IN SEMICONDUCTOR MANUFACTURING

| Process | Process Description | Hydrogen Use |
|---------------------------|--|--|
| Polysilicon Production | Silicon is produced by the pyrolytic decomposition of trichlorosilane or silicon tetrachloride by the following reaction: $\text{H}_2(\text{g}) + \text{SiHCl}_3(\text{g}) \rightarrow \text{Si}(\text{s}) + 3\text{HCl}(\text{g})$ | Reducing agent |
| Crystal Growth | The production of single crystals (usually silicon) from a melt of polycrystalline starting material. The two most common crystal growth methods are the Czochralski method and the Float Zone method. | Atmosphere |
| Epitaxy | The process of depositing a crystalline layer having the same structure as the substrate. Impurities such as diborane or phosphine are often added to the epitaxial layers to change the electrical conductivity of the crystalline silicon. | Reducing medium and/or carrier gas |
| Etching | Removing unwanted material from a surface. | Atmosphere |
| Oxidation | Growing a layer of silicon dioxide on a silicon surface. | Hydrogen and oxygen are combined to make pyrogenic steam |
| Diffusion | A high-temperature process in which dopants are introduced into the surface layer of the semiconductor material to change its electrical characteristics. | Carrier gas |
| Chemical Vapor Deposition | The process of forming a thin film on a substrate by the chemical reaction of a gaseous species (epitaxy is a special form of chemical vapor deposition). | Carrier gas and reducing atmosphere when the substrate is polycrystalline silicon or one of the III-V elements |
| Ion Implantation | A technique for doping impurity atoms into an underlying substrate by accelerating the selected dopant ion toward the silicon target through an electrical field. | Dilution of dopant bearing gases |
| Annealing | The slow regrowing of a crystal from amorphous material through the application of heat. This process is commonly used to relieve stress after the substrate has been bombarded by accelerated ions. | Atmosphere |
| Bonding | Attachment of an integrated circuit's electrical circuits to the external environment. | Atmosphere |

Hydrogen Sources for Electronics Uses

Because of its high purity, liquid hydrogen has traditionally been the form of choice for consumers purchasing hydrogen for wafer fabrication and polysilicon production.

Purity requirements for hydrogen for fuel use are not as stringent, which means that a company's procurement decision will be based primarily on production and transportation economics. Quartz fabricators tend to be small volume consumers that will purchase gas in tube trailers. AT&T is the largest fiber optic manufacturer that uses hydrogen. AT&T purchased liquid hydrogen at its Norcross, Georgia facility until its requirements grew large enough to justify having Union Carbide operate an on site system at the site.

Regional Consumption

The electronics industry, in particular integrated circuit manufacture, tends to be concentrated in the Western states, the South Central region and the Northeast. Fiber optics has been a large end use in the South Atlantic states, polysilicon production in the Western and North Central states, and quartz production in the North Central and South Atlantic states.

Factors Affecting Consumption for Electronics Uses

Liquid hydrogen consumption has not grown as rapidly as the electronic industry segments that consume hydrogen, primarily due to increased efficiency of use. For example, polysilicon production used to be a large market for liquid hydrogen, but unit requirements were vastly reduced in the early 1980s by the introduction of hydrogen recycling. It is believed that unit hydrogen consumption for wafer fabrication will increase slightly because of the trend toward CMOS and BiCMOS structures that are heavily dependant on epitaxy in their processing. Hydrogen has also been proposed as part of a system to replace CFCs used in cleaning solutions. Liquid hydrogen consumption in electronics is projected to grow at an average annual rate of 4.5% to 5.0% from 1989 to 2000.

FATS AND OILS

Table 9 displays consumption in the fats industry, and projections for the next ten years.

Table 9
LIQUID HYDROGEN CONSUMPTION IN FATS AND OILS

| Year | Millions of Cubic Feet | Average Annual Growth |
|-------------|-----------------------------------|----------------------------------|
| 1980 | 1,060 | |
| 1985 | 940 | -2.4% (1980-1985) |
| 1987 | 900 | |
| 1988 | 870 | |
| 1989 | 910 | -0.8% (1985-1989) |
| 1990 | 870 | |
| 1995 | 1,085-1,185 | 3.0% to 4.5% (1989-1995) |
| 2000 | 1,299-1,480 | 3.5% to 4.5% (1995-2000) |

Fats Applications

Hydrogenation increases the ratio of saturated to unsaturated bonds, which in turn affects the chemical and physical properties of fats and oils. Hydrogenated products are less susceptible to oxidation and subsequent spoilage. Hydrogenation raises the melting point of a fat or oil, so oils that are normally a liquid at room temperature can remain as solids at room temperature.

✦ The U.S. fats and oils industry can be divided roughly into two segments: the segment classified under SIC code 207 that is primarily involved hydrogenating vegetable oils for use in products such as shortening, margarine, baking fats, and frying fats, and the segment manufacturing chemical products such as fatty acids from tallow or vegetable oils for use in shampoos, industrial lubricants, household cleaners, and other applications. Consumption for fatty acid manufacture is discussed in the chemical industry sector.

Hydrogen Sources for Fats Uses

An estimated 8 to 9 billion cubic feet of hydrogen are consumed annually in the hydrogenation of fats and oils. The vast majority of hydrogen is produced captive. Companies with captive facilities typically produce enough hydrogen for all their needs, so hydrogen purchases are limited to supplying demand when the hydrogen plant is closed for maintenance once or twice a year. Maintenance is usually scheduled for slow periods, and generally does not take more than two days. During this time, most captive producers will purchase one or two truckloads of liquid hydrogen. Most of the plants that do not produce hydrogen purchase liquid hydrogen, although one plant in the Northwest is known to purchase by-product gas.

Regional Consumption

Demand for this end use is concentrated in the North Central region, which accounted for an estimated 45% of liquid consumption in 1989.

Factors Affecting Consumption for Fats Uses

Production of hydrogenated fats and oils has increased at an average annual rate of about 2.7% over the past 10 years and should continue to grow at an average annual rate of about 1.5-2.5% from 1990 to 2000. Liquid hydrogen consumption in this industry has not followed trends in fats production. From 1980 to 1985, several larger companies expanded their market share and consolidated production at large facilities with on-site generators. Although a few companies with smaller hydrogen plants, generally based on ammonia dissociation or electrolysis, converted to purchased gas or liquid product, this did not compensate for the decline in liquid hydrogen consumption that took place as large liquid accounts converted to on-site production and some smaller liquid hydrogen accounts ceased production.

From 1985 to 1990, consumption has fluctuated between 870 and 940 million cubic feet. In any given year, demand is less likely to reflect industry growth than one-time incidents, such as whether a fats processing plant has opened or closed or switched between captive and purchased product. For example, the primary factors influencing the change in consumption between 1989 and 1990 were the installation of a captive hydrogen plant at the Ag Processing Inc., St. Joseph, MO, facility, combined with the construction of the new Aarhus Inc. facility in Port Newark, NJ, that will use purchased hydrogen.

It is expected that liquid hydrogen consumption in the fats and oils industry will grow at an average annual rate of 3.0% to 4.5% from 1989 to 1995, and at an average annual rate of 3.5% to 4.5% from 1995 to 2000. Assumptions behind this projection include the following:

- The trend toward industry consolidation, and in turn toward large plants with captive hydrogen, has slowed.
- Hydrogen consumption per unit product will not decline and may increase.
- Recently developed fat substitutes, such as Simplex from Monsanto Co. and Olestra from Proctor & Gamble, will remain comparatively small volume specialty products and will not erode the market for natural fats.

Hydrogen consumption per unit product is difficult to predict since several factors, often contradictory, influence the amount of hydrogen consumed per unit of product. These factors include changes in the degree of hydrogenation desired as well as changes in the efficiency of the hydrogenation process.

One major factor that affects the degree of hydrogenation required is change in the types of oils processed, which is in turn influenced by world vegetable oil prices and consumer preferences. For example, in the mid-1980s comparatively low prices for palm oil led to large increases in its use. Because palm oil was more saturated than most of the oils it replaced, less hydrogenation was required.

In recent years, health concerns have led to a consumer preference for unsaturated fats; this can lead to an increase in hydrogenation levels since unsaturated fats in many instances require

partial hydrogenation to obtain necessary physical characteristics. The fast food industry, which has historically used large quantities of fats that are naturally highly saturated, is considering converting to less saturated vegetable oils which will need to be partially hydrogenated for use.

In theory, developments in biotechnology could make it possible to breed plants from which oils of the proper degree of saturation would be produced without further modifications but this is not likely to impact hydrogen consumption by 2000.

GLASS

Table 10 displays consumption in the glass industry, and projections for the next ten years.

Table 10
LIQUID HYDROGEN CONSUMPTION IN FLOAT GLASS

| Year | Millions of Cubic Feet | Average Annual Growth |
|-------------|-------------------------------|------------------------------|
| 1980 | 685 | |
| 1985 | 700 | 0.4% (1980-1985) |
| 1987 | 720 | |
| 1988 | 750 | |
| 1989 | 760 | 2.1% (1985-1989) |
| 1990 | 710 | |
| 1995 | 795-910 | 0.8% to 3.0% (1989-1995) |
| 2000 | 855-1,055 | 1.5% to 3.0% (1995-2000) |

Glass Applications

Hydrogen is used as an oxygen scavenging atmosphere in the manufacture of flat glass by the float process. In the float process, a continuous ribbon of glass is floated on a bed of molten tin. Because tin is highly sensitive to oxidation, the glass is held in a controlled atmosphere of nitrogen and hydrogen while the irregularities in the glass even out and the glass becomes flat. The glass is then cooled while it advances across the molten tin until the glass surface is hard enough for the glass to be removed. A typical float atmosphere is 5 to 6% hydrogen and 94 to 95% nitrogen, although the hydrogen concentration can vary between 3% and 8%. Hydrogen concentrations as high as 10% have been used on occasion.

Hydrogen Sources for Glass Uses

Because their annual requirements are below the point where it is economic to produce hydrogen, all consumers in this industry currently purchase liquid hydrogen. In the early 1980s, Guardian Industries purchased by-product gaseous hydrogen from a chlorine-sodium hydroxide

plant near its Carleton, Michigan facility. Since the closure of that plant in early 1985, Guardian has purchased liquid product.

During the next five to ten years it is expected that glass consumers will continue buying liquid hydrogen from industrial gas suppliers. Consumers report that even if technology were available to produce hydrogen captively in the quantities consumed in this industry, that they would be reluctant to invest the capital necessary to build, operate, and maintain a hydrogen plant.

Regional Consumption

Most hydrogen for float glass production is consumed in the North Central region (30% of 1989 consumption), followed by the South Central and South Atlantic regions (24% and 22%, respectively), and then the West and Northeast (13% and 11%, respectively).

Float glass tanks tend to be located near glass markets. For example, glass demand for the automotive industry is concentrated in the North Central region. The newest float glass plants have been built in the Western and South Atlantic states to supply demand associated with increased construction. In the South Atlantic region, half of the U.S. mirror glass manufacturing industry is located within approximately 150 miles of the Libby Glass's North Carolina plant.

Factors Affecting Consumption for Glass Uses

Hydrogen consumption tends to vary with two factors: float glass production and the concentration of hydrogen in the controlled atmosphere. Float glass production levels are by far the most important factor.

Float glass production reached record levels in 1987 and 1988 and several new plants came on stream; (PPG Industries in Chehalis, WA, in late 1986; AFG Industries in Victorville, CA, in late 1987; Guardian Industries in Richburg, SC, in late 1988; AFG Industries Inc. in Spring Hill, KS, in January 1989; PPG Industries in Cumberland, MD, in late 1989). In 1989, production levels remained flat. Because capacity grew more rapidly than demand, some older facilities were temporarily closed in 1990 for maintenance (e.g., one of Ford's tanks at Tulsa, OK and Libbey's unit at Lathrop, CA) or to avoid building up excessive inventories (e.g., AFG Industries at Cinnaminson, NJ, and one of three tanks at Ford's Nashville, TN facility). Float glass tanks tend to operate near capacity or not at all.

In general, companies try to minimize hydrogen consumption to control costs. Since 1980, companies have become more efficient in their hydrogen use. It appears unlikely that significant further reductions in hydrogen consumption will take place.

Between 1989 and 1995, liquid hydrogen consumption in float glass production is expected to increase at an average annual rate of 0.8% to 3.0%. Between 1995 and 2000 consumption is forecast to increase at an average annual rate of 1.5% to 3.0%.

Regional growth is not expected to vary significantly from the national trend. None of the major U.S. companies have announced new plant construction over the next five years, although it is expected that the lines that are currently not operating will come back on stream. Currently the West and South Atlantic are the regions least likely to build new plants since these are the areas where new plants were most recently constructed. The West is especially experiencing overcapacity currently. The West also has strict environmental regulations regarding furnace

emissions which increase the costs associated with operating a plant in the region. In Pennsylvania, a study was done for a new float glass facility by a group of investors not currently in the float glass business, but plans for building an actual plant have not been initiated.

OTHER USES

Table 11 displays hydrogen consumption for other, marginal users of hydrogen.

Table 11
OTHER CONSUMPTION OF HYDROGEN

| Year | Millions of Cubic Feet |
|-------------|-----------------------------------|
| 1980 | 160 |
| 1985 | 160 |
| 1987 | 340 |
| 1988 | 265 |
| 1989 | 380 |
| 1990 | 425 |
| 1995 | 495-515 |
| 2000 | 600-830 |

This category includes consumption at public utilities for generator cooling, and controlling stress corrosion cracking at nuclear power plants with boiling water reactors. Other applications include calibration gas for instrumentation, and a variety of processes requiring a controlled atmosphere, including in various research activities. As in other industry sectors, some of the demand consumption is attributed to unusual short term requirements. For example, one producer reported selling liquid hydrogen for its fuel value over a five day period during a cold spell last winter when fuel supplies were unusually tight. Because consumption in this category (which accounts for less than 5% of total consumption) is obtained by difference, fluctuations in the data reflect any imprecision in the records of consumption in the individual market sectors, as well as actual changes in consumption.

In the long term, there are tremendous opportunities for hydrogen as an alternate energy source or energy carrier. Despite ongoing research in this area, it is not anticipated that energy will become a significant market for hydrogen in the U.S. by 2000. Even if hydrogen should achieve widespread use as an alternate energy source or energy carrier, it is unclear in what form the hydrogen would be consumed. For example, a vehicle powered by a hydrogen fueled fuel cell could generate the hydrogen on board from methanol. Alternatively, gaseous hydrogen could be stored in metal hydrides or other materials, such as the activated carbon being studied by Syracuse University. Most sources involved in development of alternate fueled vehicles report that the fear of consumer rejection of a system based on hydrogen has limited the development of vehicles

fueled directly by hydrogen. It is thought that many individuals are only aware of hydrogen for its role in the Hindenburg disaster, and would be unlikely to want a hydrogen tank on their car. In general, liquid hydrogen is most likely to be required for projects that involve large scale or nonterrestrial transport, such as the proposed project for sending energy from Quebec to Western Europe, and studies concerning hydrogen for use as an aircraft fuel.

The province of Quebec in Canada and the European Community are currently studying the feasibility of shipping hydrogen to Hamburg, West Germany. Under the current proposal, the hydrogen would be produced electrolytically at a 100 megawatt plant in Quebec on the St. Lawrence Seaway. The hydrogen could be shipped as liquid hydrogen, ammonia, or methylcyclohexane. The initial phase of the project, which is nearing completion, will estimate the cost of the concept with an accuracy of about 15%. On a preliminary basis, industry sources indicate that shipping liquid hydrogen currently appears to be the most promising alternative. However, it also appears that transporting hydrogen from Quebec to Hamburg, as opposed to producing hydrogen in Hamburg, is unlikely to be justifiable on purely economic grounds. Once the initial studies are complete, there is no funding mechanism in place for implementing the program. Because it is highly uncertain whether the idea will be implemented, and because hydrogen for the project would be produced from a dedicated plant, it is assumed that this project will not impact the North American market for liquid hydrogen between now and 2000.

Industry sources indicate that development of hydrogen as a fuel for commercial aircraft is unlikely to take place before development of the National Aerospace Plane, since expertise gained from development of the aerospace plane could be transferred to commercial aircraft. This would push development of commercial hydrogen fueled aircraft beyond 2000. It is possible that small scale aircraft, such as the unmanned aircraft for atmospheric research applications proposed by Aurora Flight Sciences Corporation, could consume liquid hydrogen by 2000. Current estimates put hydrogen consumption at 300 pounds per flight for the Aurora. If the concept is in fact developed, it is unlikely that more than one or two flights would take place before 2000.

International demand has placed and will continue to place only minor demands on U.S. plants. It is expected that Canadian plants will continue to represent a significant source of liquid hydrogen to the commercial sector.

In 1989, trade with Canada is estimated to have resulted in the net import of 2,700 million cubic feet (19.3 tons per day) of liquid hydrogen. This hydrogen primarily served liquid hydrogen demand in the Northeast and North Central regions.



Report Documentation Page

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|---|--|---|-----------|
| 1. Report No. NASA TM 103812 | 2. Government Accession No. | 3. Recipient's Catalog No. | |
| 4. Title and Subtitle An Assessment of the Government Liquid Hydrogen Requirements for the 1995-2005 Timeframe Including Addendum, Liquid Hydrogen Production and Commercial Demand in the United States | | 5. Report Date July 1990 | |
| | | 6. Performing Organization Code SI | |
| 7. Author(s) Addison Bain Barbara Heydorn (Addendum) | | 8. Performing Organization Report No. | |
| | | 10. Work Unit No. | |
| 9. Performing Organization Name and Address NASA, John F. Kennedy Space Center Kennedy Space Center, FL 32899 | | 11. Contract or Grant No. | |
| | | 13. Type of Report and Period Covered Technical Memorandum 1990 | |
| 12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546 | | 14. Sponsoring Agency Code | |
| | | | |
| 15. Supplementary Notes | | | |
| 16. Abstract <p>Hydrogen, particularly liquid hydrogen, will continue to be an integral element in virtually every major space related program as well as numerous aeronautical programs and a variety of research projects throughout the United States. Liquid hydrogen has also become a significant merchant product to serve certain commercial markets requiring bulk hydrogen for providing many consumer goods and services.</p> <p>Liquid hydrogen is not a universally available commodity (production) as compared to other commonly used cryogenics and industrial gases. The number of supply sources historically have been limited to regions having concentrated consumption patterns. Namely this has been the Southwest, Southeast, and Northeast regions. Except for the Northeast, which is predominantly a commercial demand area, production plant location and size were typically gauged by needs contemplated by the government.</p> <p>With the increased space program activity and the possible reality of new programs it becomes necessary to assess all future programs on a collective and unified basis to assure that proper planning and contractual commitments are timely to meet everyone's needs. This report is an initial attempt to identify projected requirements on a long range basis.</p> | | | |
| 17. Key Words (Suggested by Author(s)) Liquid Hydrogen | | 18. Distribution Statement Unclassified - Unlimited | |
| 19. Security Classif. (of this report) Unclassified | 20. Security Classif. (of this page) Unclassified | 21. No. of pages | 22. Price |

